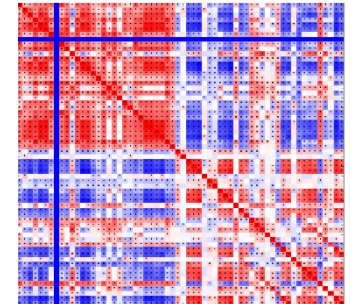
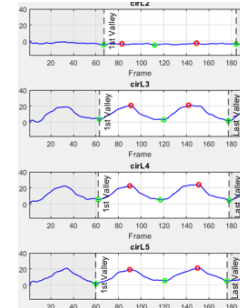
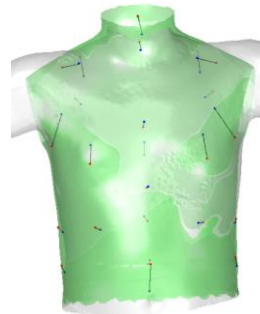
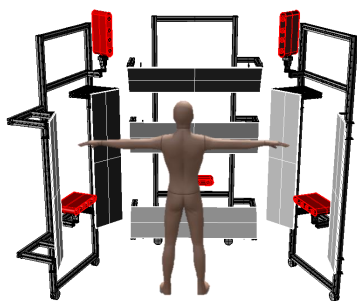




# Development of a 4D Scanning-Based Method for Respiratory Motion Analysis in Patients with Diaphragm Dysfunction



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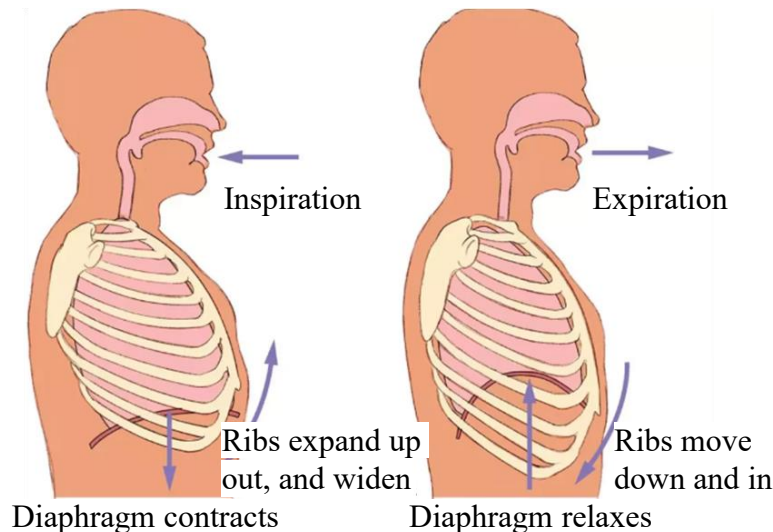
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- **Introduction**
    - ❖ Background
    - ❖ Study Objectives
  - **Method**
    - ❖ 4D Scanning-Based Experimental Protocol
    - ❖ Respiratory Motion Analysis
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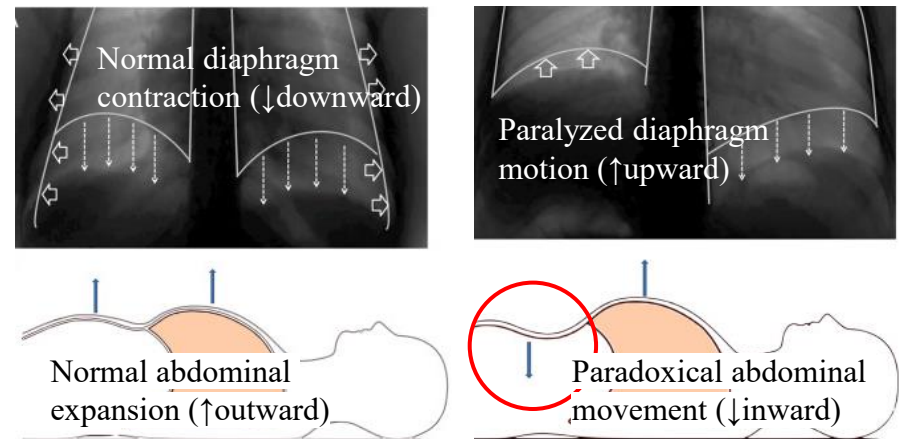
# Diaphragm Dysfunction (DD)

- ❑ DD refers to **impaired** or **paralyzed diaphragm movement**, leading to reduced **inspiratory efficiency** and **decreased lung ventilation**, which **leads to breathing difficulty**.
- ❑ DD can be anatomically classified into unilateral paralysis, bilateral dysfunction, and complete or partial impairment based on the **laterality** and **severity of muscular involvement**.

## Mechanics of breathing



## Motion patterns of the diaphragm and abdomen during inspiration: normal vs. DD

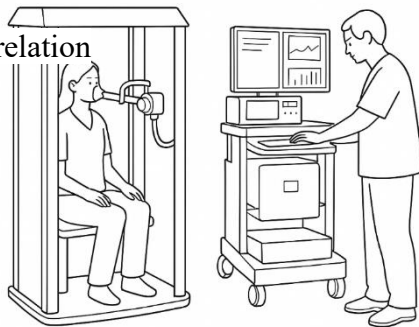


# Diagnosis of DD

- ❑ **Pulmonary function testing (PFT)** and **diaphragm ultrasound (DU)** are commonly used for the **clinical diagnosis** of DD
  - ❑ **Limitations:** (1) **operator dependency**, (2) **localized anatomical assessment**, and (3) **insufficient spatiotemporal resolution**
- ⇒ **Need** for more **accurate**, **comprehensive**, and **operator-independent diagnostic tools**

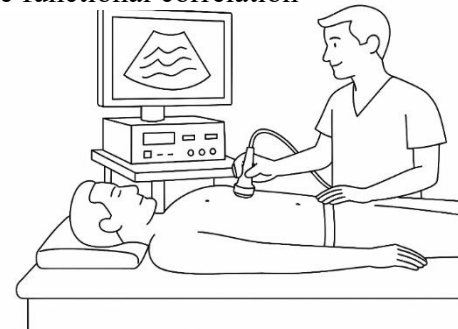
## PFT

- ✓ No spatiotemporal info
- ✓ No regional abnormality detection
- ✓ Requires patient effort (forced exhalation)
- ✓ Numeric only
- ✓ Strong functional correlation



## DU

- ✓ Localized diaphragm movement
- ✓ Operator dependent
- ✓ Single movement trace
- ✓ Moderate functional correlation



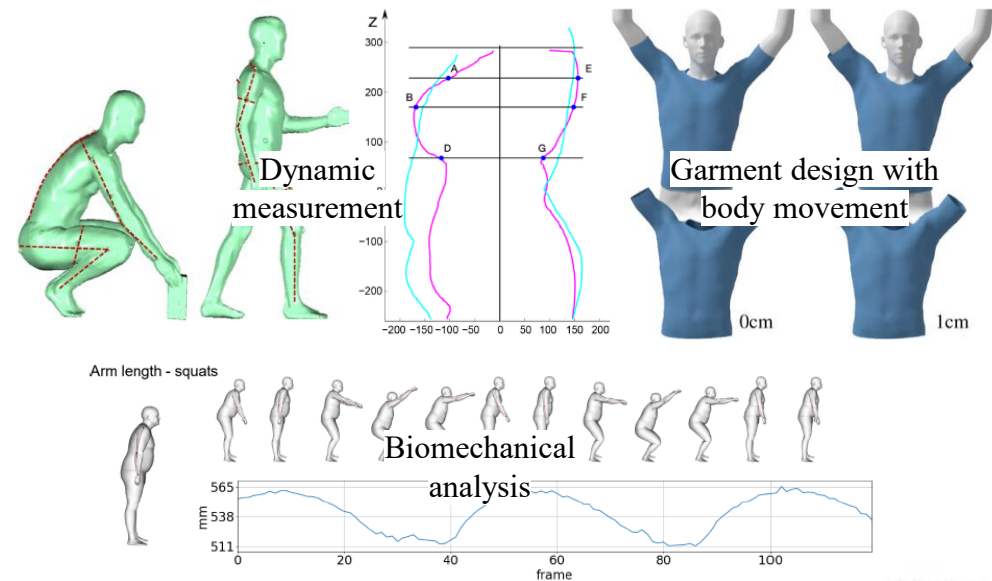
# 4D Scanning

- ❑ **4D** (or temporal 3D) **scanning** refers to **continuous 3D scanning** of a subject **over time** to capture **dynamic motion** or **shape changes**.
- ❑ 4D scanning data have been applied in fields such as **dynamic anthropometry**, **ergonomic product design** and **evaluation**, and **biomechanical motion analysis**.

## Acquisition of dynamic motion data using 4D scanning system (3dMD, 3dMD Inc., GA, USA)



## Applications of 4D scanning data



# Objectives

## Development of a 4D Scanning-Based Method for Respiratory Motion Analysis in Patients with DD

1. **Collection of 4D respiratory motion data and clinical assessment data**
2. **Geometry measurement and respiratory feature extraction**
3. **Comparison of respiratory patterns between patients and healthy controls**
4. **Correlation analysis between 4D features and clinical assessments**

# Research Procedure

**S1. Collection of 4D respiratory motion and clinical assessment data**



**S2. Preprocessing of 4D scanning data and feature extraction**

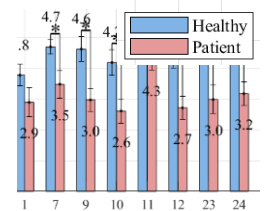
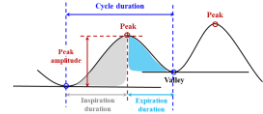
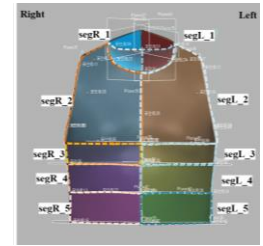


**S3. Comparison of respiratory patterns between patients and healthy controls**



**S4. Correlation analysis between 4D features and clinical assessments**

- ✓ 4D scanning of torso and neck movement during deep breath (DB) and tidal breath (TB)
- ✓ PFT & DU
- ✓ Template registration-based measurement (LM displacement, circumference, area, volume)
- ✓ Respiration motion feature extraction (geometry, inspiration/expiration (I/E) ratio, cycle time)
- ✓ Comparison of peak displacement & circumference & area & volume, inspiration/expiration (I/E) ratio, cycle time
- ✓ Correlation analysis between 4D features and PFT (FVC, FEV1/FVC) & DU (diaphragm excursion)



# S1. Data Collection: Participants

- **8 healthy subjects** and **8 patients** with **DD (right-sided paralysis** or **bilateral dysfunctions more severe on the right)** were recruited.

Summary of patient demographics and associated clinical diagnoses

No.	Gender	Age	Height	Weight	Clinical diagnosis
P01	M	63	171	63.0	Idiopathic pulmonary fibrosis
P02	M	69	177	55.5	Idiopathic pulmonary fibrosis (right diaphragm complete palsy)
P03	M	64	173	54.0	Lung transplantation (bilateral diaphragm dysfunction, more severe at right)
P04	M	50	170	64.0	Thymoma (right diaphragm complete paralysis, tracheostomy)
P05	M	52	169	68.0	Lung transplantation (right diaphragm paralysis))
P06	F	80	153	62.0	Interstitial lung disease (right diaphragm dysfunction)
P07	M	61	167	46.0	Liver transplantation (right diaphragm palsy)
P08	M	66	174	60.0	Tracheostomy (bilateral diaphragm dysfunctions, more severe at right)

# S1. Data Collection: Clinical Assessment

## ❑ DU (Diaphragm Ultrasound)

✓ **Diaphragm excursion**: vertical movement of the diaphragm

⇒ Used to estimate **diaphragmatic paralysis degree**

## ❑ PFT (Pulmonary Function Test)

✓ **Forced vital capacity (FVC)**: the maximum capacity of air that a patient can exhale after a maximum inspiration

✓ **Forced expiratory volume in 1s/ FVC (FEV1/FVC)**: ratio of air exhaled in the first second to total forced vital capacity

⇒ Used to assess **lung capacity** and identify **obstructive or restrictive patterns**

### DU measurements in supine position

3. Ultrasound

1. Supine

1) excursion

	Tidal breath	Deep breath
	Resting (cm)	Forced (cm)
Right	2,41	5,22
Left	2,91	5,18

**Diaphragm excursion**

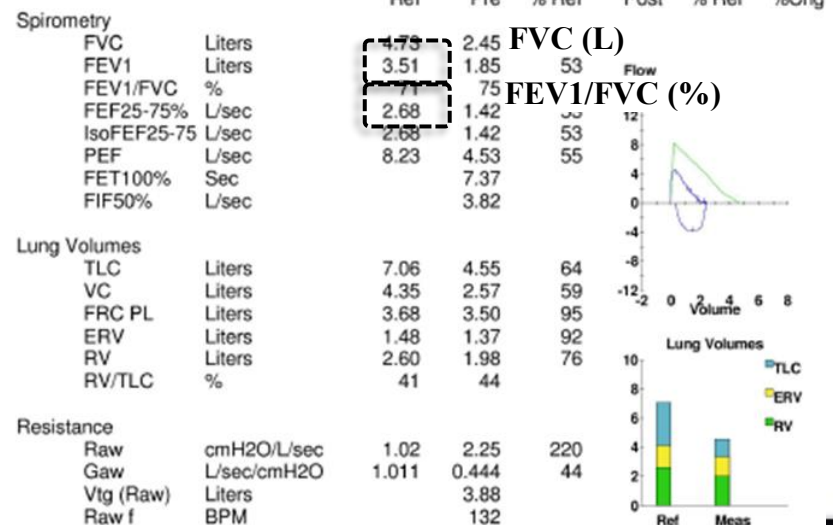
2) thickness

Right end-expiratory (cm)	Right end-inspiratory (cm)	Thickness fraction
0,17	0,23	0.35294

Left end-expiratory (cm)	Left end-inspiratory (cm)	Thickness fraction
0,16	0,24	0.5

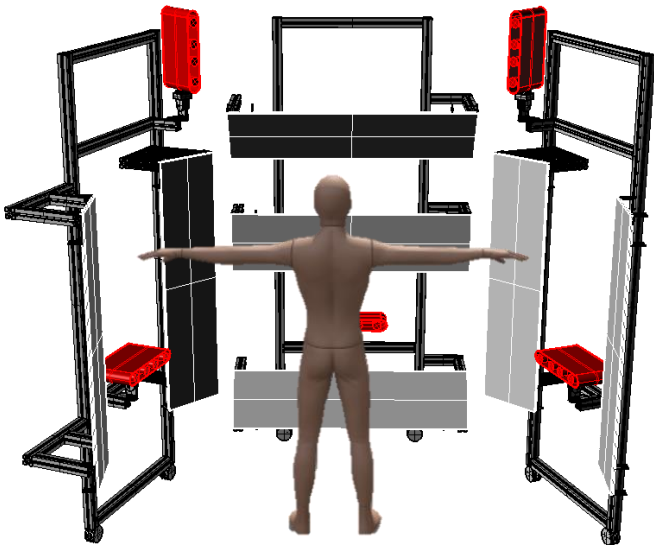
### PFT results



# S1. Data Collection: 4D Scanning

- **Upper-body movements** during **deep breathing (DB)** and **tidal breathing (TB)** were captured using **4D scanning system** (3dMD, 3dMD Inc., Atlanta, GA, USA) (10fps, linear accuracy  $\geq 0.7\text{mm}$ ) across **196 to 199 frames** during **20s**.

4D scanning environment



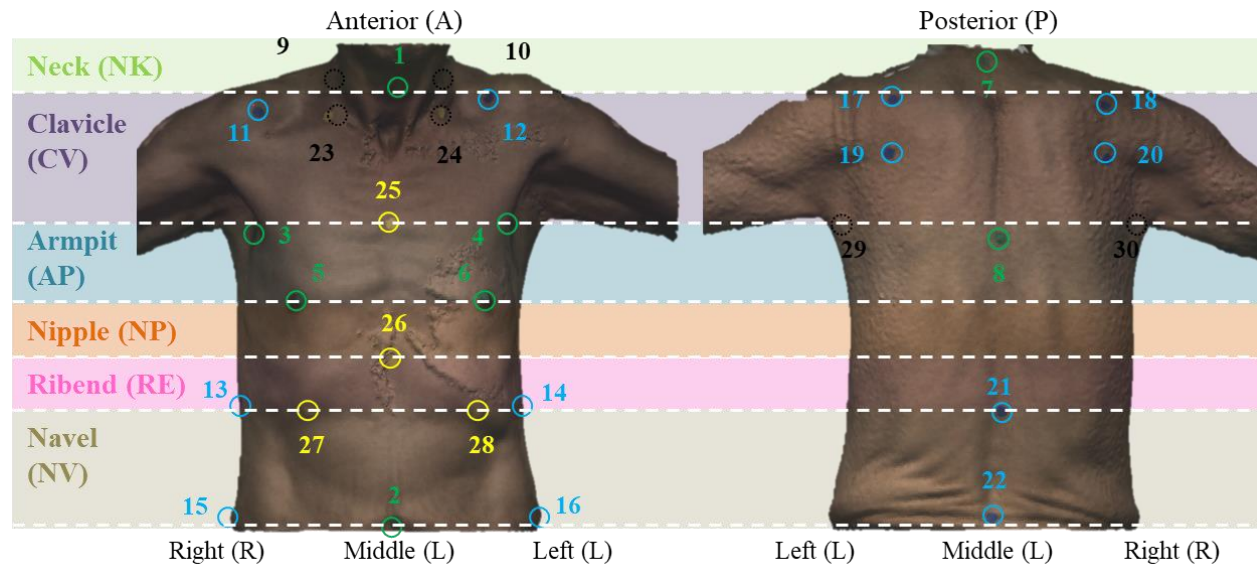
4D scans



# S1. Data Collection: Landmark (LM) Placement

- Before 4D scanning, **30 anatomical landmarks** (LMs) were placed on the **upper-body** using **color stickers** applied through **palpation**.

No.	Code	No.	Code
LM1	NK_A_M	LM16	NV_A_L
LM2	NV_A_M	LM17	CV_P_LU
LM3	AP_A_R	LM18	CV_P_RU
LM4	AP_A_L	LM19	CV_P_LL
LM5	NP_A_R	LM20	CV_P_RL
LM6	NP_A_L	LM21	RE_P_M
LM7	NK_P_M	LM22	NV_P_M
LM8	AP_P_M	LM23	CV_A_RP
LM9	NK_A_R	LM24	CV_A_LP
LM10	NK_A_L	LM25	AP_A_M
LM11	CV_A_RD	LM26	RE_A_M
LM12	CV_A_LD	LM27	RE_A_RP
LM13	RE_A_RD	LM28	RE_A_LP
LM14	RE_A_LD	LM29	AP_P_L
LM15	NV_A_R	LM30	AP_P_R



# S2. Geometry Measurement & Respiratory Feature Extraction: Procedure

## S2-1. Geometry measurement



## S2-2. Geometry signal preprocessing

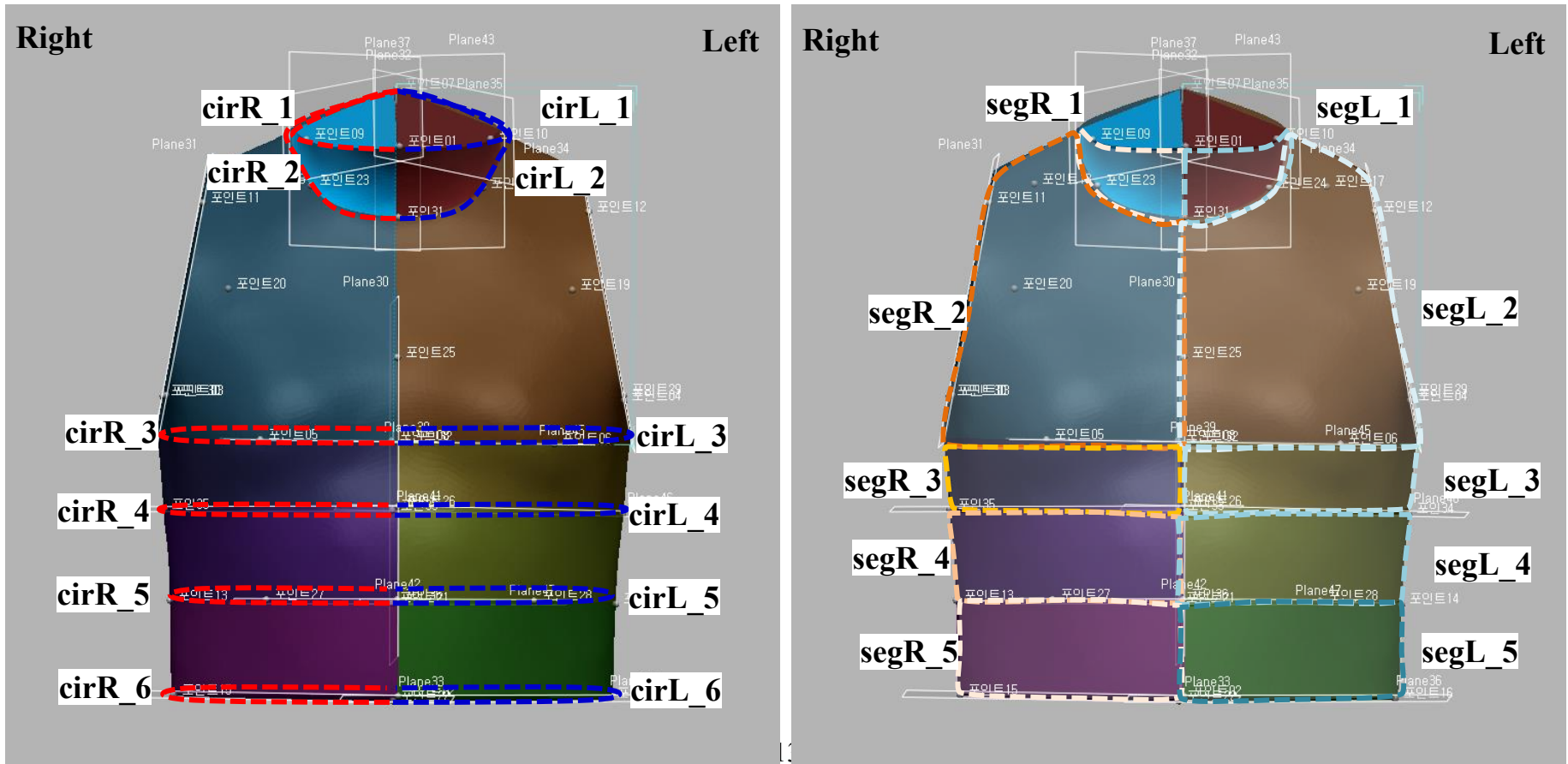


## S2-3. Respiratory feature extraction

- ✓ Semi-auto color-based LM detection, alignment
- ✓ Template-registration based geometry measurement: displacement, circumference, area, volume
- ✓ Spline interpolation (for missing data)
- ✓ Savitzky–Golay filtering (for data smoothing)
- ✓ Baseline correction (aligned to resting frame)
- ✓ Reference peak/valley detection (global)
- ✓ Local peak/valley detection (per signal)
- ✓ Cycle-based respiratory feature extraction: peak displacement, inspiration/expiration/cycle duration

# S2-1. Geometry Measurement Definition

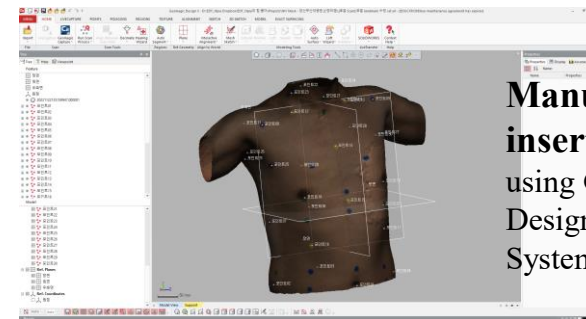
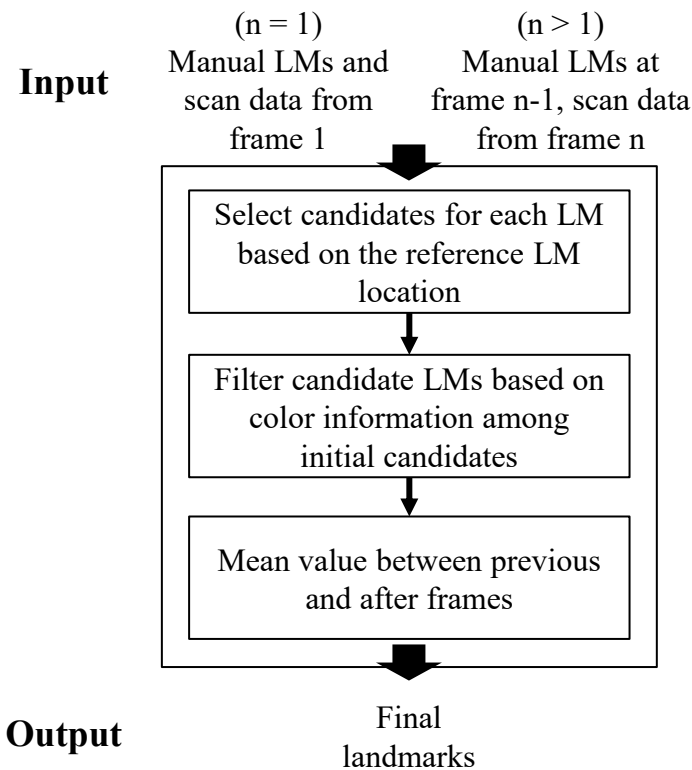
- A total of **12 circumferences**, **10 areas**, and **10 volumes** were defined for geometric analysis, covering both the right and left segments.



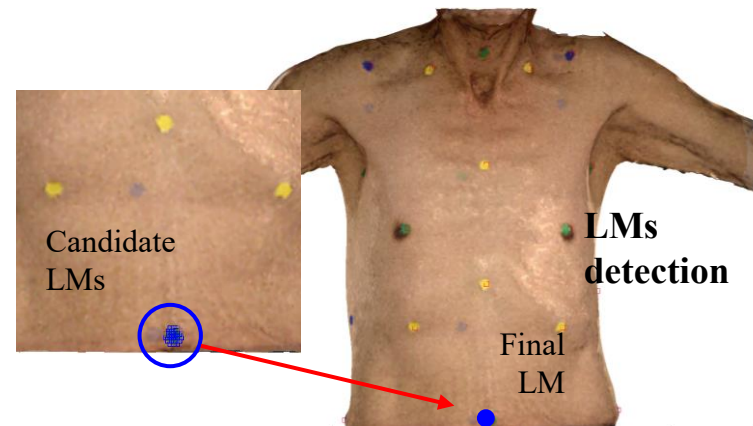
# S2-1. LM Detection

- LMs were detected using a **semi-automatic method** based on **initial landmark locations** and the **color information of the stickers**.

## Semi-automatic LM detection



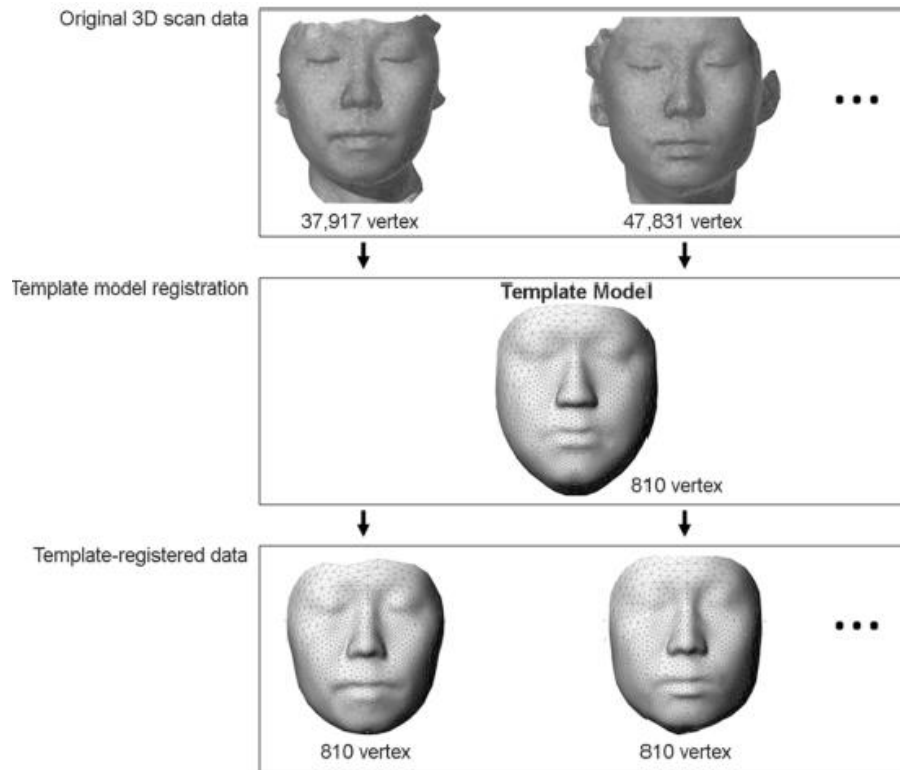
**Manual insertion of LMs** using Geomagic Design X (3D Systems, SC, USA)



## S2-1. Template Registration Method (1/4)

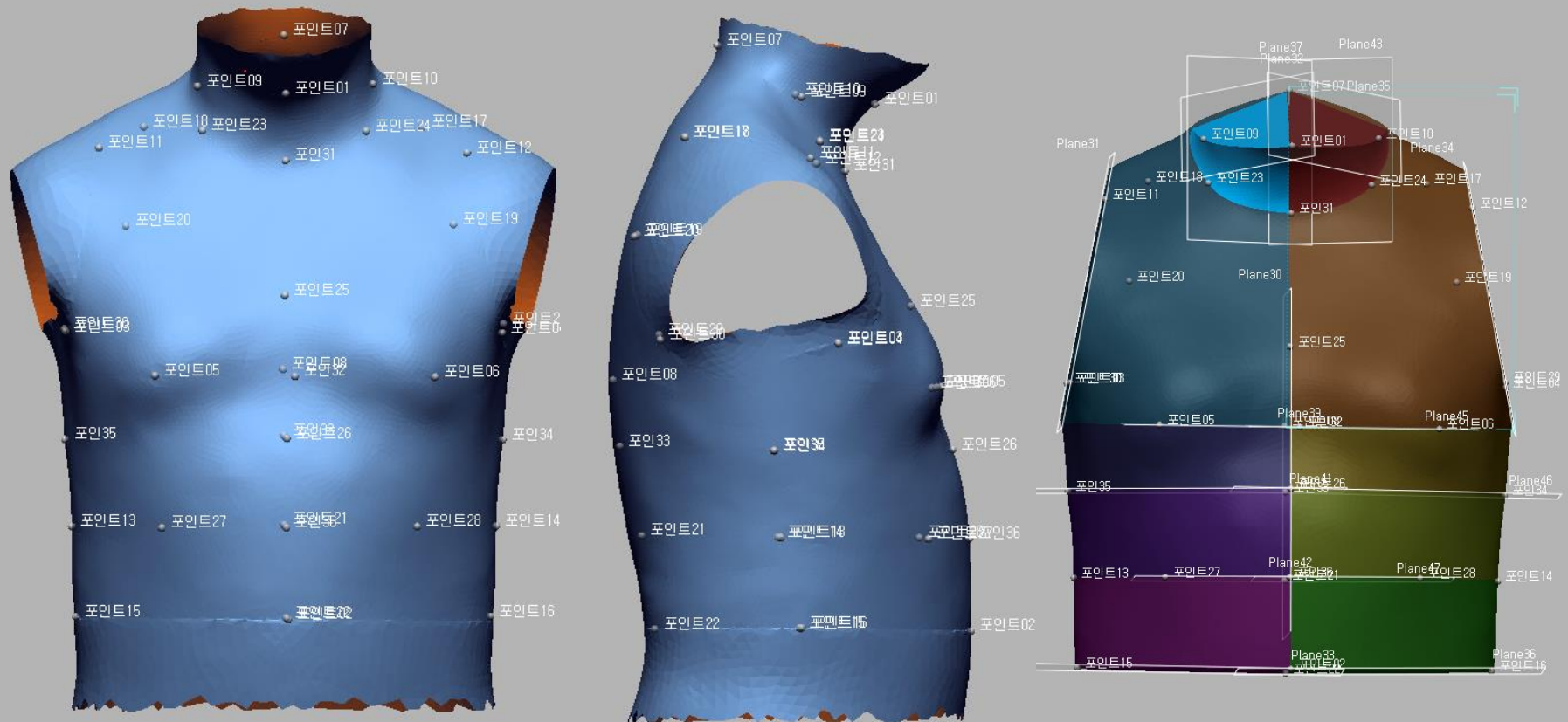
- ❑ **Template registration technique** matches a **template image** to its corresponding 3D scan image and **maintain** the **mesh structure** and **features** (ex. shape, vertex, and LMs) of the template image.

Example of template registration of the face



## S2-1. Template Construction (2/4)

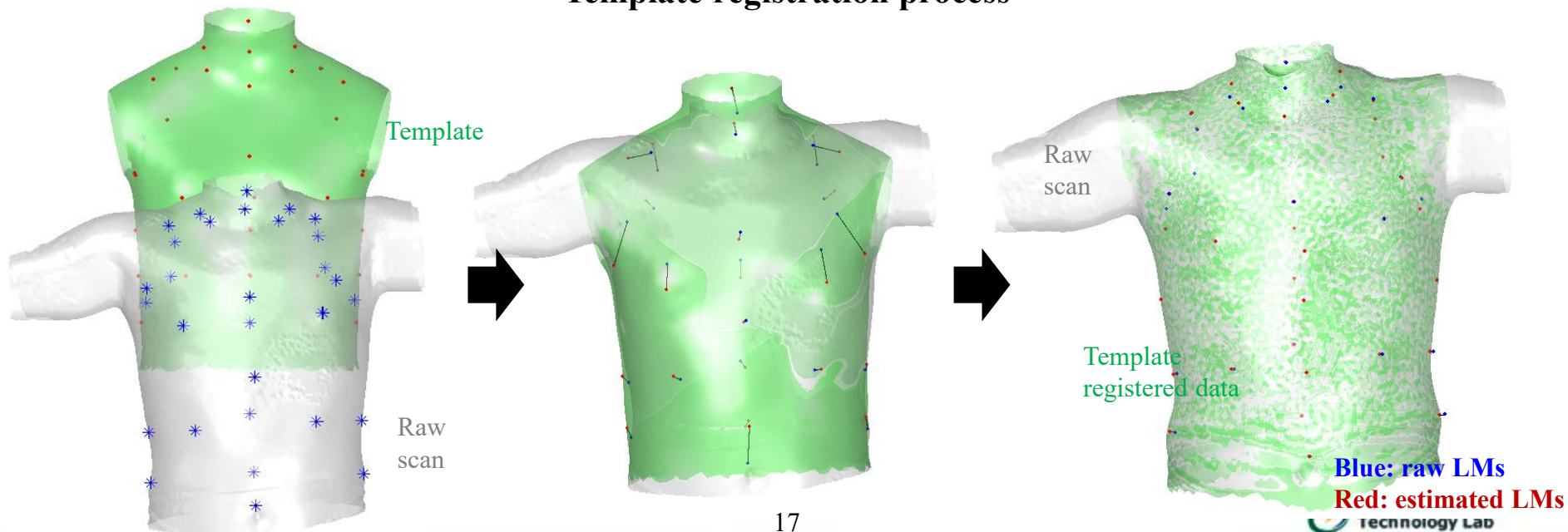
- A **template mesh** was constructed with **embedded 36 LMs**, including 24 basic LMs for template registration and 12 estimated LMs for measurement (only 6 for analysis), along with **10 predefined areas**.



## S2-1. Template Registration-Based Geometry Measurement (3/4)

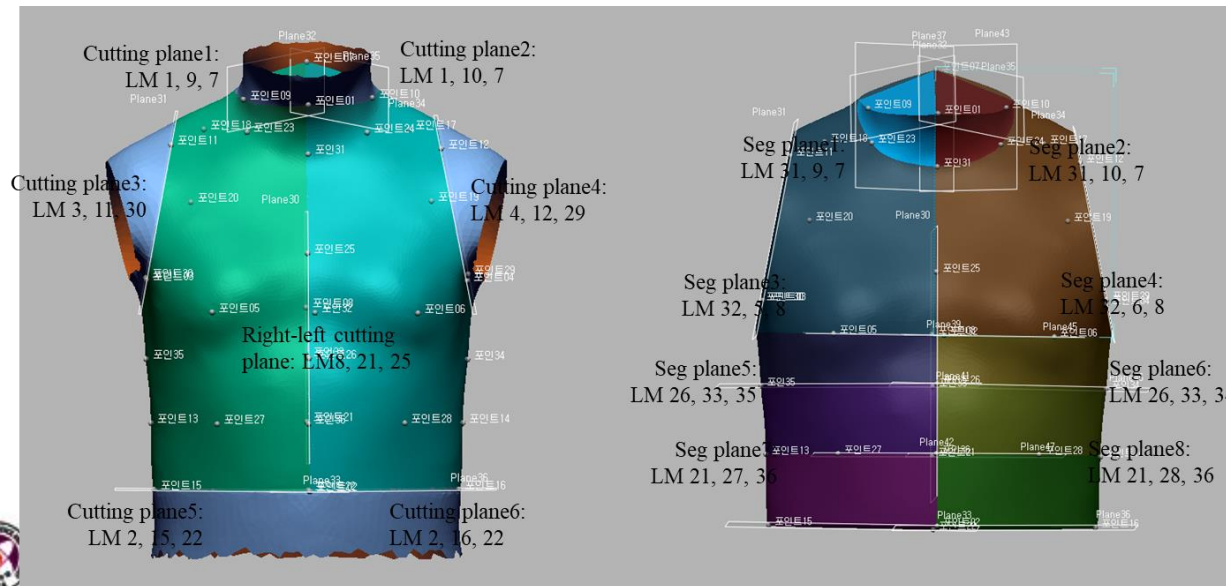
- ❑ The **template registration method** was applied **using 24 LMs** to **estimate 12 LMs** and directly **measure 10 areas**.
  - ❑ **12 circumferences** and **10 volumes** were measured based on the **registered LMs**
- ⇒ The template registration method helps address issues related to **missing** or **insufficiently** detected LMs.

Template registration process



# S2-1. Template Registration-Based Geometry Measurement (4/4)

- ❑ **30 LM displacements, 12 circumferences, 10 areas, and 10 volumes** were extracted from on both the right and left sides across **sequential frames**.
- ✓ **LM displacement:** Euclidean distance between LM locations.
- ✓ **Circumference:** sum of segmented surface curves, each defined by projecting the shortest path between three LMs onto a plane.
- ✓ **Area:** surface regions enclosed by predefined landmark indices, which formed closed boundaries suitable for surface integration.
- ✓ **Volume:** enclosed mesh segment between cutting planes.



		Frame1			Frame2			Frame3		
		X	Y	Z	X	Y	Z	X	Y	Z
NK_A_M	LM01	-9.94	163.90	191.31	-7.51	165.44	191.94	-7.29	164.36	191.50
HP_A_M	LM02	18.76	-266.71	221.35	9.69	-267.07	221.32	9.04	-267.91	220.70
AP_A_R	LM03	-145.17	40.41	175.69	-148.16	42.20	174.43	-148.06	42.83	174.80
AP_A_L	LM04	125.81	158.07	156.65	129.57	154.45	183.34	126.48	55.80	185.64
NP_A_R	LM05	-91.44	193.91	206.83	-93.77	193.03	208.44	-93.77	-12.58	207.88
NP_A_L	LM06	163.27	9.97	206.83	163.85	6.73	206.85	163.34	7.91	208.41
NK_P_M	LM07	-9.66	193.91	72.75	-4.43	193.03	72.66	-5.02	193.33	72.67
CV_A_M	LM31	-10.58	130.24	183.97	-5.48	130.86	183.96	-6.79	130.43	189.22
NP_A_M	LM32	12.25	-26.60	236.64	9.96	-25.95	236.60	9.10	-26.07	236.37
NP_P_M	LM33	0.46	-58.37	-2.26	0.00	-57.94	-2.22	-0.02	-58.45	-2.16
XP_A_LD	LM34	166.58	-60.64	119.72	166.31	-65.14	121.47	165.64	-65.49	122.03
XP_A_RD	LM35	-154.57	-83.51	117.35	-154.97	-80.02	115.08	-155.45	-79.52	114.96
KE_A_M	LM36	14.62	-168.78	243.50	8.57	-169.65	243.76	7.65	-170.44	243.47

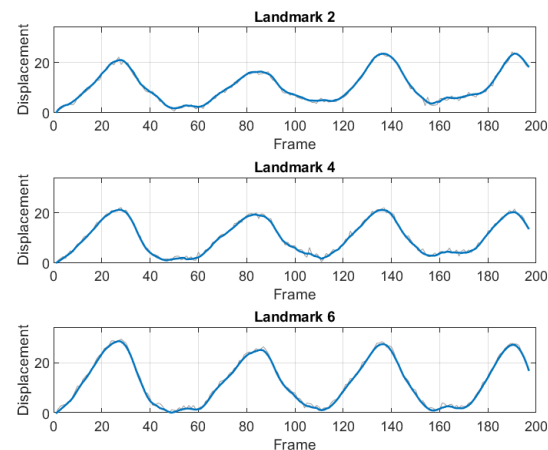
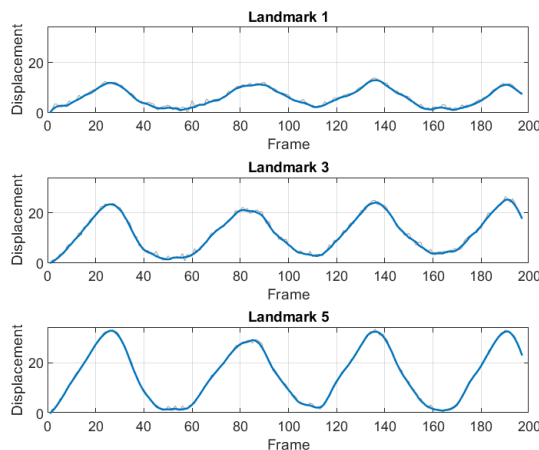
  

vwr1	93281.43	94578.34	92995.76	95631.70	94017.29	95384.31	95155.85	97374.79	96136.30
vwr2	2482142.85	2437864.78	2418269.25	2428196.27	2409818.14	2430669.68	246814.55	2429112.03	2441231.18
vwr3	1667836.70	1657471.49	1662081.54	1644564.23	1630088.31	1668400.67	1632373.12	1644837.94	
vwr4	217231.83	2167382.92	2189482.32	2147034.66	2160051.33	2181830.88	2146211.68	2181832.32	2193023.49
vwr5	2323633.39	2327782.12	2315131.52	2319505.19	2320971.80	2348949.25	2311984.48	2346816.74	2356671.59
vwr6	2475313.48	2454957.64	2465237.02	2452222.82	2432926.96	2494194.27	2528153.38	2531613.38	2483711.74
vll1	64792.96	74386.32	70767.27	74652.93	61889.47	59820.69	64674.46		
vll2	237037.68	2399923.15	2392381.90	239282.42	2314431.72	2382468.02	2326249.57	2316016.97	2317662.08
vll3	1497795.12	1492124.54	1474879.13	1480610.01	1465861.57	1472827.02	1488741.23	1463992.98	1438279.46
vll4	2355151.06	2340132.92	2365351.20	2348861.04	2337028.29	2340061.18	2352264.56	2350661.68	2357862.59
vll5	2303991.42	2480594.59	2420311.18	2477117.94	2466688.02	2420020.07	2452429.83	2452971.73	2466683.18
vll6	329994.04	3249148.25	3231004.59	3260396.54	3260050.99	3233621.49	3291272.75	3274932.22	3287910.25
area1	3810.35	2907.72	3882.36	2929.22	2892.39	2873.18	3913.75	2925.86	2858.17
area2	3717.46	31320.14	34873.83	35207.58	34888.29	31603.47	31923.12	31388.75	31336.61
area3	17456.77	17310.48	17317.59	17999.81	17294.61	16995.35	17468.85	17028.23	17175.28
area4	3089.98	30904.29	31211.34	30647.59	30922.58	31153.04	30791.41	31233.93	31374.44
area5	3206.45	31800.51	31406.00	31581.19	31911.90	32409.69	31887.39	32233.55	31972.56
area6	3755.17	38802.07	39127.20	38449.35	37571.24	38683.19	38571.40	38264.15	
area7	2308.24	2024.10	2571.35	2324.77	2044.46	2040.03	2014.48	2351.85	
area8	3161.55	32086.85	32323.37	32299.73	31912.40	31937.91	32081.83	31540.15	31511.60
area9	14604.78	14804.18	14433.60	14433.70	14312.79	14429.92	14575.02	14340.33	14037.16
area10	3093.98	31196.58	31383.67	30960.46	31080.68	31377.66	31434.35	30753.03	31387.28
area11	3209.59	32428.71	31789.97	3212.72	32279.10	31965.15	31410.34	32008.06	32005.50
area12	46599.81	46477.73	44848.31	46343.68	47428.00	46682.95	47055.18	47007.77	47032.15
area13	207.97	207.97	207.97	207.97	207.97	207.97	207.97	207.97	207.97
area14	211.37	218.34	216.01	212.17	215.15	217.17	215.16	218.32	214.05
area15	470.05	469.17	468.00	469.24	468.89	468.01	467.98	468.74	470.03
area16	468.18	454.69	458.03	453.37	455.29	456.19	455.75	456.56	456.56
area17	440.70	433.91	434.64	432.86	433.61	435.31	432.86	434.44	433.50
area18	457.36	444.36	446.00	445.88	445.88	445.88	447.06	442.70	443.61
area19	199.87	194.11	194.11	194.11	194.11	194.11	194.11	194.11	194.11
area20	211.06	207.42	210.20	212.19	211.60	210.15	213.00	209.65	211.80
area21	452.87	455.73	458.04	452.27	454.72	453.70	454.23	454.81	451.66
area22	468.48	472.23	471.63	471.62	471.56	471.56	472.22	471.60	472.96
area23	453.69	439.23	439.23	439.23	439.97	437.85	438.05	439.47	439.88
area24	453.77	467.40	468.16	467.38	467.67	468.96	466.51	467.37	466.36

## S2-2. Geometry Signal Preprocessing

- ❑ **Geometry signals** were **preprocessed** through **outlier removal**, **interpolation**, **smoothing**, and **baseline correction** to **enhance signal quality**.
  - 1) **Outlier removal**: using  $Z\text{-score} > 3$  with local median (window = 5)
  - 2) **Spline interpolation**: filling missing values using spline interpolation along the time axis
  - 3) **Savitzky-Golay filter**: smoothing data with a polynomial of degree 3 and a window size of 11
  - 4) **Baseline correction**: standardizing the baseline using the value of first/resting frame

### Geometry signal preprocessing example (e.g., LM displacement)

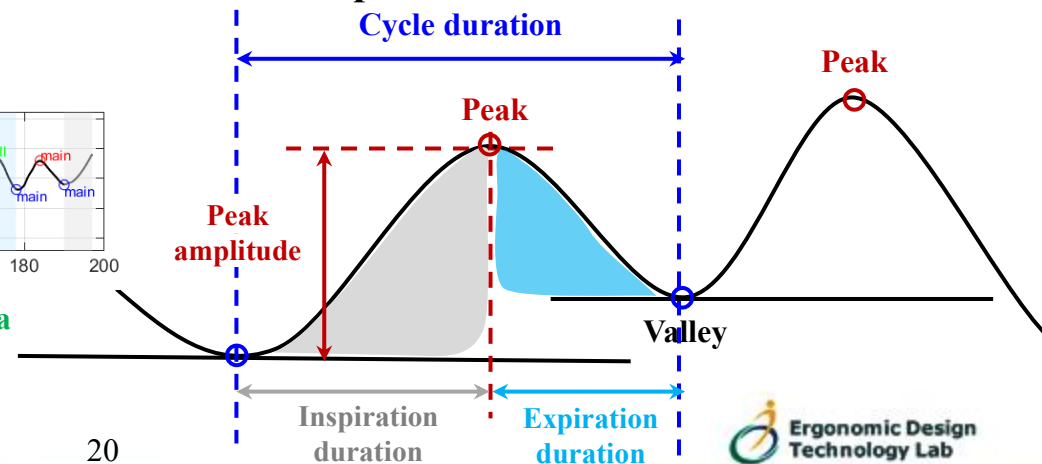
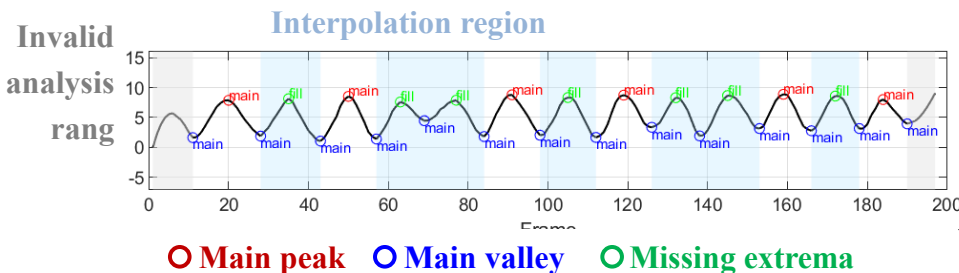


— Raw  
— Preprocessed

## S2-3. Respiratory Feature Extraction

- **Peak amplitude, inspiration/expiration time (I/E ratio), cycle duration** for each cycle for each geometry signal including **LM displacement, circumference, area, volume** were extracted independently
  - 1) **Main peak/valley detection:** identify prominent peaks & valleys using thresholds on prominence and distance
  - 2) **Missing extrema completion:** insert opposite extrema between consecutive same-type extrema
  - 3) **Analysis window definition:** use the first valley/peak to define valid range
  - 4) **Cycle-based feature extraction:** Extract respiratory features on a valley-to-valley (or peak-to-peak) basis

### Respiratory feature extraction process



# S3 & S4. Respiratory Motion Analysis: Statistical Analysis

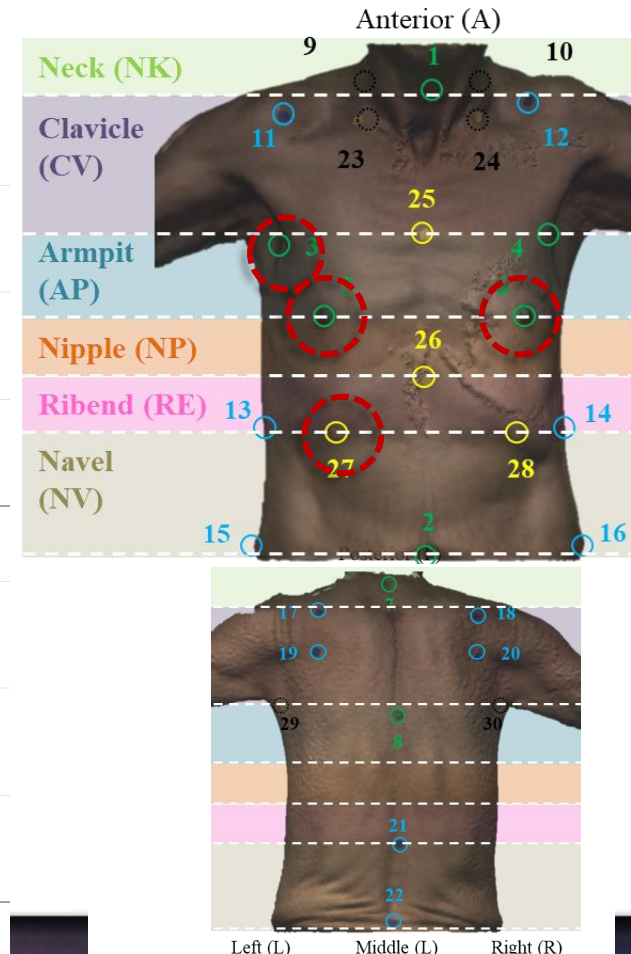
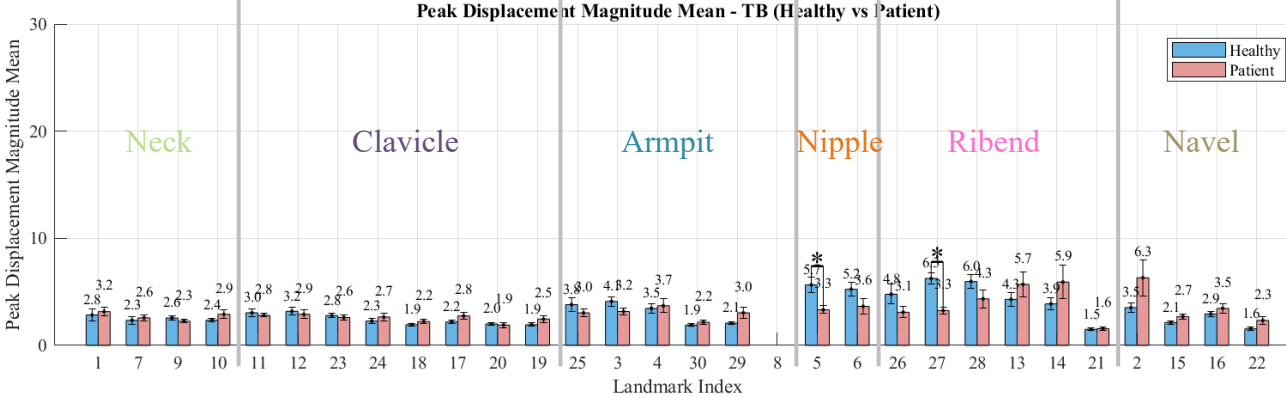
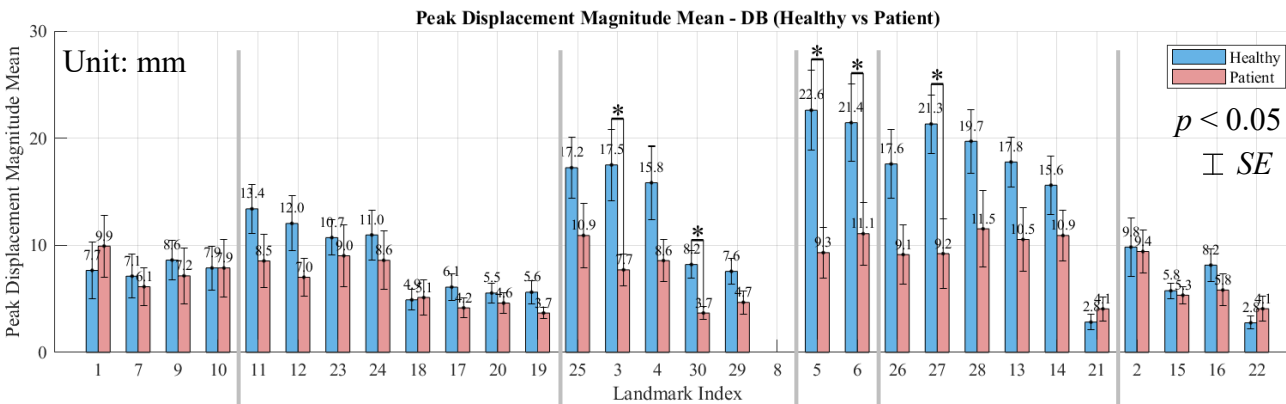
- ❑ **Group comparisons between patients and healthy controls** were conducted using **Welch's t-test** (two-sample unpaired t-test,  $p < 0.05$ ) for each LM.
  - ✓ **4D geometry features:** peak displacement
  - ✓ **Temporal features:** cycle duration
  
- ❑ **Pearson correlation analysis** was performed to examine the linear relationships between **4D features** and **clinical measures** (PFT and DU) for each LM.
  - ✓ **Peak displacement vs. FVC**
  - ✓ **I/E ratio vs. FEV1/FVC**
  - ✓ **Peak displacement vs. diaphragm excursion**

# Result: Group Differences in 4D Geometry (Ex. Peak Displacement)

❑ **Patients** demonstrated **significantly reduced peak displacement** than **healthy subjects** in **several LMs**

✓ **DB:** LM03 (↓55.9%), LM05 (↓58.8%), LM06 (↓48.3%), LM27(↓56.8%)

✓ **TB:** LM05 (↓41.0%), LM27 (↓47.9%)

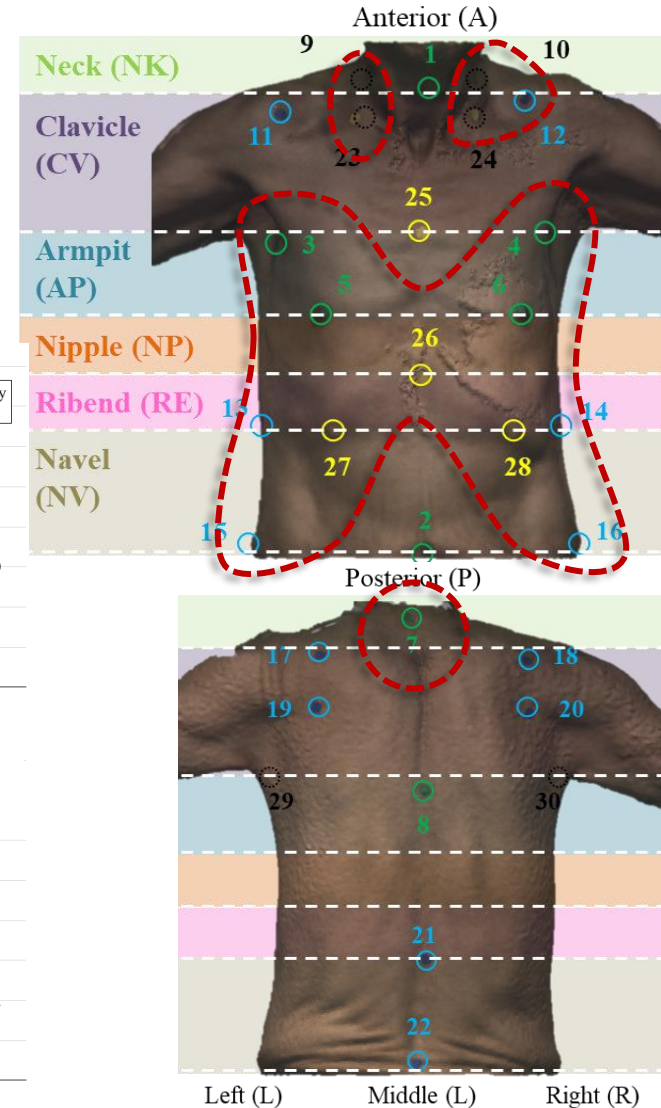
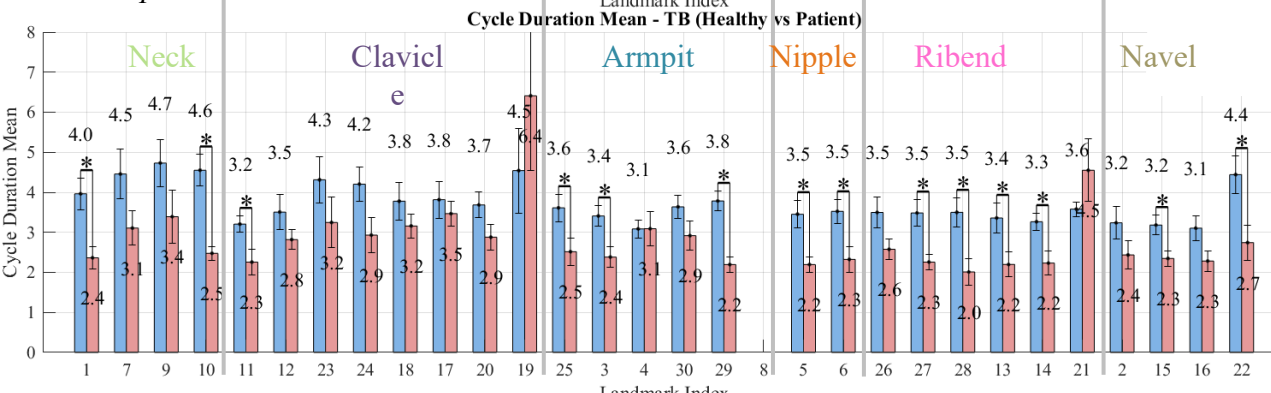
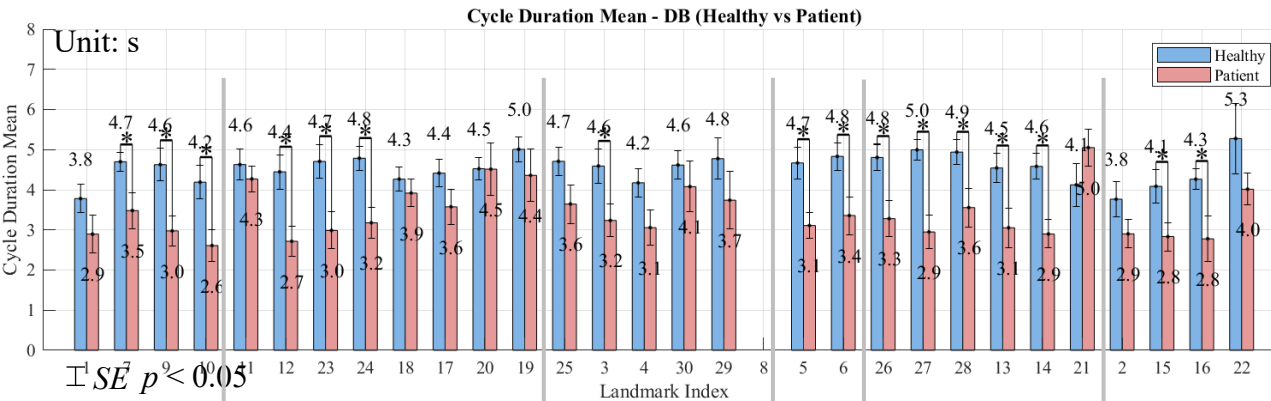


# Result: Group Differences in Cycle Duration

❑ **Patients** exhibited **shorter respiratory cycle durations** than **healthy subjects** across most **LMs**, especially in **anterior LMs**

✓ **DB: H (4.5s) patient >> P (3.4s), ↓ 24.9%**

✓ **TB: H (3.7s) patient >> P (2.8s), ↓ 24.2%**



# Results: Correlation Between 4D Geometry and PFT (Ex. Peak Displacement vs. FVC)

- Peak displacement shows **strong positive correlation** with **FVC** during **DB** (most  $r > 0.7$ ), but the **correlation weakens** or **disappears** during **TB**.

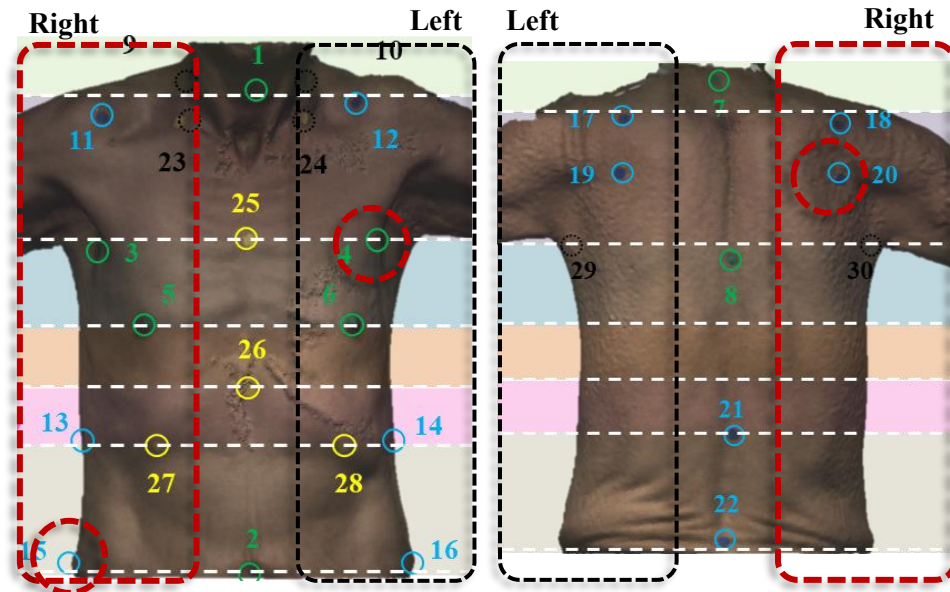
⇒ Large peak displacement during DB reflects better FVC, while TB-related displacement is less indicative of lung function.

- R20** shows **strong positive correlation** ( $r = 0.86$ ) even during **TB**.

⇒ Partial preservation of functional movement in R20 region.

Peak displacement vs. FVC

DB	R09	R11	R23	R20	R18	R03	R30	R05	R13	R27	R15	L10	L12	L24	L19	L17	L04	L29	L06	L14	L28	L16	
	0.70	0.67	0.73	0.86	0.77	0.77	0.47	0.85	0.74	0.76	0.97*												
TB	0.19	0.43	0.44	0.86*	0.11	0.39	0.32	-0.06	-0.27	-0.18	-0.07	-0.21	0.45	0.51	0.02	-0.09	0.41	0.46	0.18	0.24	0.22	-0.22	



# Results: Correlation Between 4D Geometry and PFT (Ex. I/E Ratio vs. FEV1/FVC)

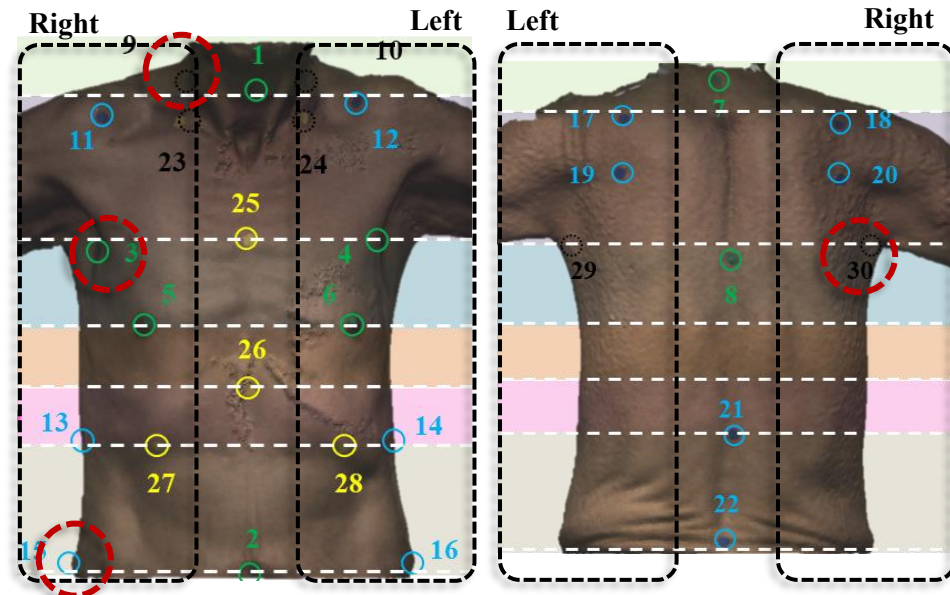
- ❑ In DB, **R03** ( $r = 0.82$ ) and **R30** ( $r = 0.83$ ) showed a **positive correlation trend** with FEV1/FVC, although not statistically significant.
  - ❑ In TB, **R09** showed a **significant positive correlation** with FEV1/FVC ( $r = 0.83$ ), while **R15** showed a **significant negative correlation** ( $r = -0.83$ )
- ⇒ Indicates that **R03 & R30** (armpit) in DB, **R09** (neck) & **R15** (navel) in TB may play a critical role in pulmonary function.

I/E ratio vs. FEV1/FVC

DB	R09	-0.28	0.34	L10
	R11	0.62	0.53	L12
	R23	-0.44	0.35	L24
	R20	-0.64	0.18	L19
	R18	-0.05	0.61	L17
	R03	0.82	0.58	L04
	R30	0.83	0.52	L29
	R05	-0.63	0.36	L06
	R13	-0.27	0.21	L14
	R27	0.48	0.52	L28
	R15	-0.10	0.58	L16

TB	R09	0.83*	-0.60	L10
	R11	-0.28	0.60	L12
	R23	-0.13	-0.20	L24
	R20	-0.10	0.45	L19
	R18	0.56	0.85*	L17
	R03	-0.16	0.09	L04
	R30	0.65	-0.04	L29
	R05	-0.48	-0.79	L06
	R13	-0.70	-0.24	L14
	R27	0.38	-0.54	L28
	R15	-0.83*	0.09	L16



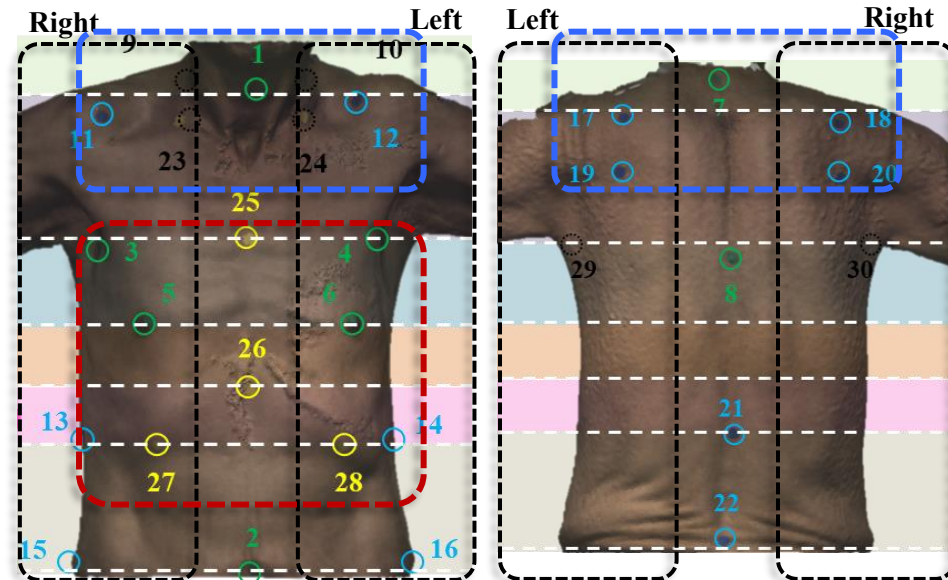
# Results: Correlation Between 4D Geometry and DU (Ex. Peak Displacement vs. Diaphragm Excursion)

- ❑ In DB, L–R asymmetry shows **negative correlation** in the **neck and shoulder region** but **positive** in the **lower thoracoabdominal region**.
- ❑ In TB, L–R asymmetry shows **positive correlation** in **lower thoracoabdominal region**.

⇒ These regional patterns suggest that L–R asymmetry may aid in detecting DD.

Peak displacement vs. diaphragm excursion

		R	L	L-R		R	L	L-R	
DB	R09/L10	-0.49	0.68	-0.33	TB	R09/L10	0.25	0.12	0.20
	R11/L12	-0.46	0.90*	-0.66		R11/L12	0.00	0.44	0.37
	R23/L24	-0.52	0.82*	-0.55		R23/L24	0.37	0.25	0.39
	R20/L19	-0.62	0.59	-0.61		R20/L19	0.02	0.49	0.49
	R18/L17	-0.56	0.40	-0.95*		R18/L17	-0.06	0.38	0.10
	R03/L04	-0.54	0.78*	0.66		R03/L04	0.30	0.52	0.55
	R30/L29	-0.53	0.71	0.44		R30/L29	-0.29	0.97*	0.89*
	R05/L06	-0.30	0.89*	0.48		R05/L06	0.48	0.68	0.59
	R13/L14	-0.18	0.88*	-0.44		R13/L14	-0.02	0.81*	0.85*
	R27/L28	-0.24	0.92*	0.50		R27/L28	0.09	0.70	0.36
	R15/L16	-0.52	0.78*	0.74		R15/L16	0.79*	-0.10	0.21



# Discussion (1/2)

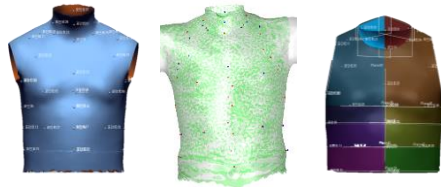
- ❑ Developed a **4D scanning-based data acquisition framework** and **template registration-based geometry extraction method** for **quantitative respiratory motion analysis**
- ❑ Demonstrated the **clinical relevance** of the proposed method by **identifying key cycle-based indicators**
  - ✓ Differentiated patients from healthy controls based on **peak displacement** and **cycle duration**
  - ✓ Showed **strong correlations** between **4D geometry-derived features** and both **PFT (FVC, FEV1/FVC)** and **DU (diaphragm excursion)**

## S1. 4D scanning



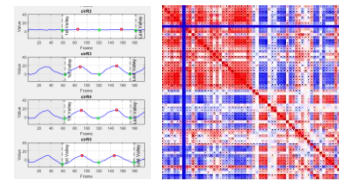
- S1-1. Palpation-based color sticker landmarking
- S1-2. 4D scanning during DB & TB

## S2. Geometry measurement



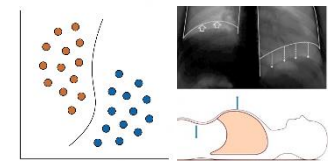
- S2-1. Color-based LM detection
- S2-2. Template registration-based geometry analysis

## S3. Feature extraction



- S3-1. Cycle-based features
- S3-2. Symmetry features

## S4. Diagnosis



- S4-1. Feature input to discriminative model
- S4.2. Diagnosis prediction

# Discussion (2/2)

❑ The proposed **4D scanning-based method** provides **cycle-based, region-specific analysis** across the **entire thoracoabdominal surface**.

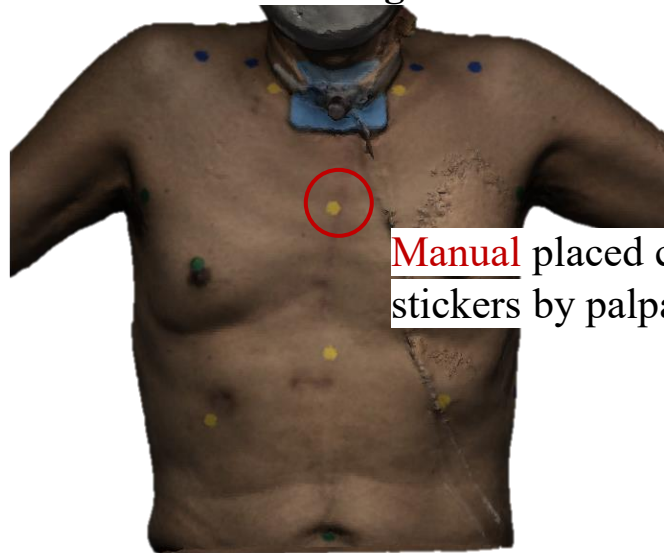
⇒ Laid the foundation for a **discriminative model** enabling DD diagnosis and monitoring, with **potential** as a **complementary tool** through **comprehensive regional respiratory assessment**.

Criteria	PFT	DU	4D scanning-based method
Measurement target	Global lung function	Diaphragm movement	Thoracoabdominal surface motion
Spatial coverage	None (no spatial info)	Localized (diaphragm only)	Full upper-body surface
Cycle-based analysis	×	Limited (single movement trace)	Yes (geometry & time)
Functional correlation	Strong	Moderate	Strong (validated via correlation to PFT/DU)
Operator dependency	Low	High	Low to moderate
Patient effort dependence	Yes (forced exhalation required)	Minimal	Minimal
Regional abnormality detection	×	Partially (diaphragm only)	Yes (multi-region differentiation)
Visualization	Numeric values only	Real-time 2D/3D imaging	Quantitative spatiotemporal motion visualization
Clinical usage	Standard, widely used	Common in clinics	Under development, research/clinical potential

# Limitation

- ❑ **Limited sample size and population diversity:** the relatively small and specific sample (8 patients and 8 healthy controls) limits both the statistical power and the generalizability of the analysis results across broader patient populations.
- ❑ **Semi-automated workflow:** the process is not fully automated, as it requires manual placement of color-coded stickers by palpation during data collection.

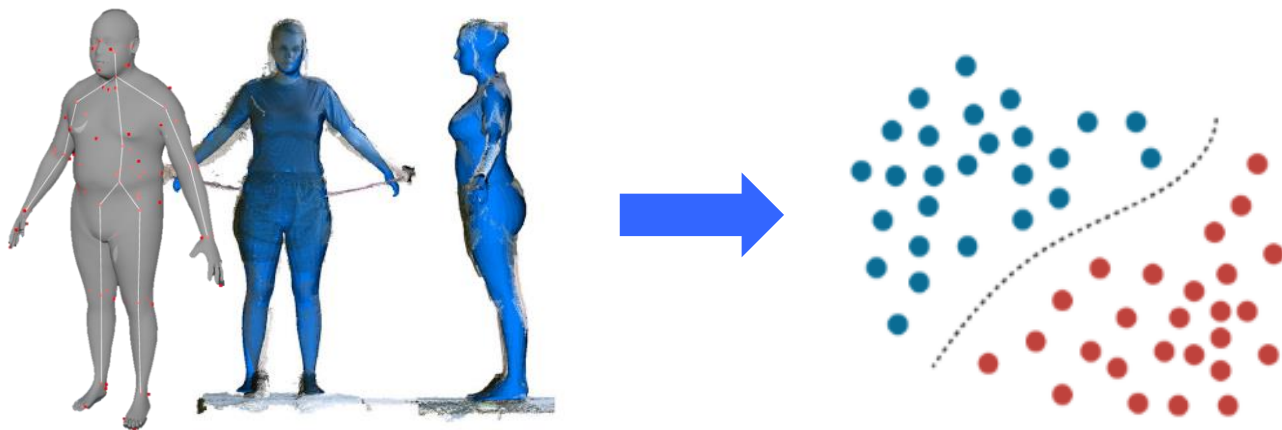
## 4D scanning data



Manual placed color stickers by palpation

# Future Study

- ❑ **Expand the sample size and diversity**: involve a **larger** and more **diverse participant** pool to enhance statistical power and generalizability across clinical populations.
- ❑ **Automate the analysis pipeline**: develop a fully automated workflow to **reduce manual intervention in landmark insertion**, increasing reproducibility and scalability.
- ❑ **Explore predictive modeling**: build **discriminative a model** (e.g., for DD classification) based on extracted respiratory features, and validate them in real-world clinical settings.



**Thank you!**



More questions to [xincui@postech.ac.kr](mailto:xincui@postech.ac.kr) (Xin Cui)