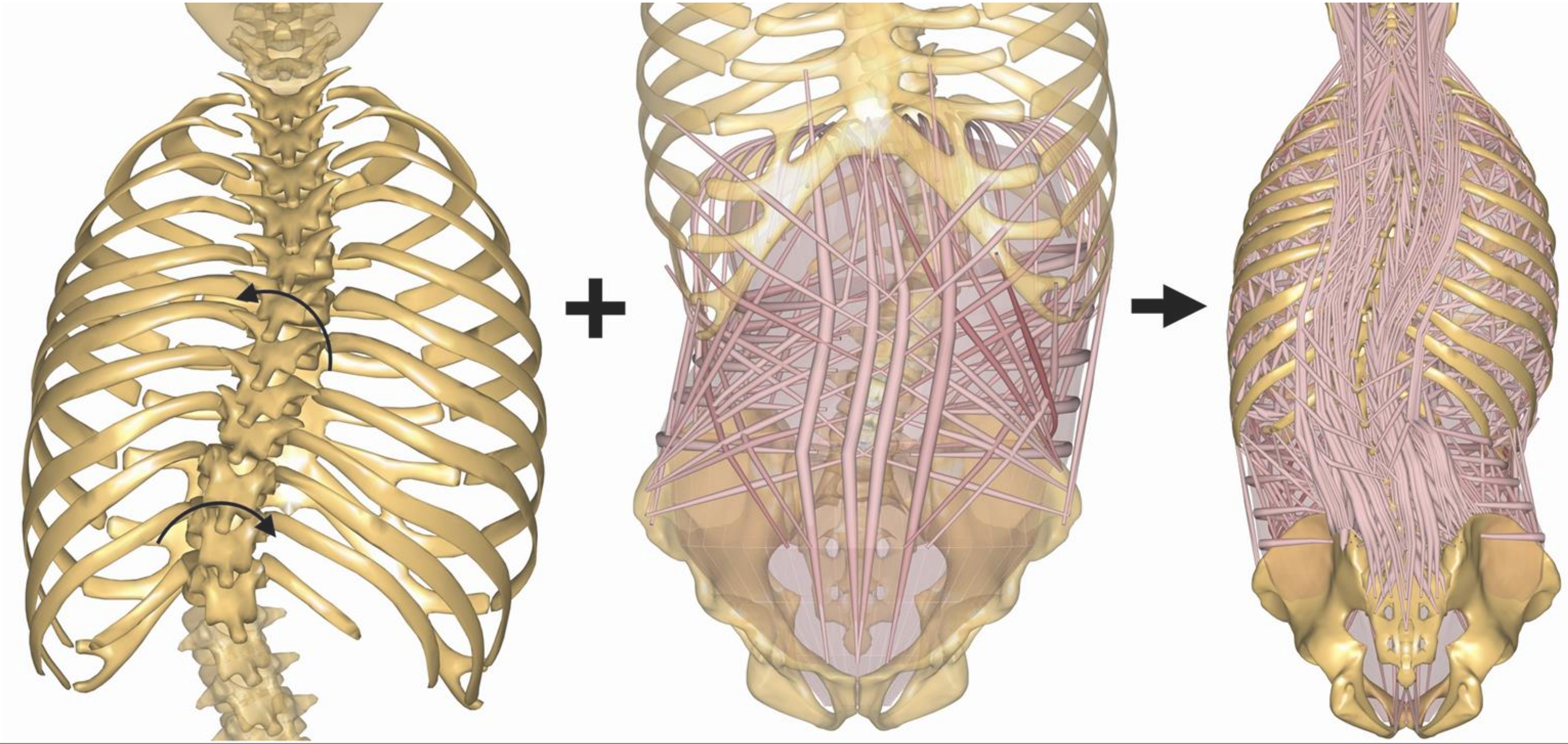


Thoracic Spine, Ribcage and Abdominal Model

in AnyBody Modeling System

Outline

- History of this study and paper list
- New thoracic spine and ribcage model
  - Spine drivers
  - Ribcage constraints
- New abdominal pressure model
  - Abdominal layers and volumes
  - Diaphragm
  - Abdomen mechanism
- Detailed muscle configuration
- Few examples
  - Bending spine and Scoliosis model
  - Thoracic MOCAP model
  - Scoliosis MOCAP model
- Q&A session

Presenter

Hamed Shayestehpour

Engineer

AnyBody Technology

Host

Kristoffer Iversen

Head of Sales

AnyBody Technology

History of this study

- Started in 2019 from my PhD in Aalborg university
  - Supervisor: Prof. John Rasmussen
  - Funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. [764644].
- Continued in AnyBody Technology from 2022

Paper list:

1. Shayestehpour, H., Rasmussen, J., Galibarov, P., Wong, C.: **An articulated spine and ribcage kinematic model for simulation of scoliosis deformities**. Multibody Syst. Dyn. 53, 115–134 (2021). https://doi.org/10.1007/s11044-021-09787-9 (Published)

Previous version of the ribcage model

2. Hamed Shayestehpour, Søren Tørholm, Michael Damsgaard, Morten Lund, Christian Wong, John Rasmussen: **A generic detailed multibody thoracic spine and ribcage model**. Multibody Syst. Dyn.

New thoracic spine and ribcage model

3. Hamed Shayestehpour, Søren Tørholm, Michael Damsgaard, Morten Lund, Christian Wong, John Rasmussen: **A generic detailed multibody abdominal and diaphragm model**. Multibody Syst. Dyn.

New abdominal pressure model

4. Hamed Shayestehpour, Mohammad Amin Shayestehpour, Christian Wong, John Rasmussen: **Kinetic investigation of a thoracolumbar spine model including the ribcage**. Journal of Biomechanics.

Detailed muscle configuration and model validation

5. Hamed Shayestehpour, Mohammad Amin Shayestehpour, Christian Wong, Jesper Bencke, John Rasmussen: **Biomechanical Analysis of Adolescent Idiopathic Scoliosis: Investigating Muscle Activation Asymmetry during Gait Using a Comprehensive Thoracic Musculoskeletal Model**. EORS conference 2024.

Scoliosis MOCAP model

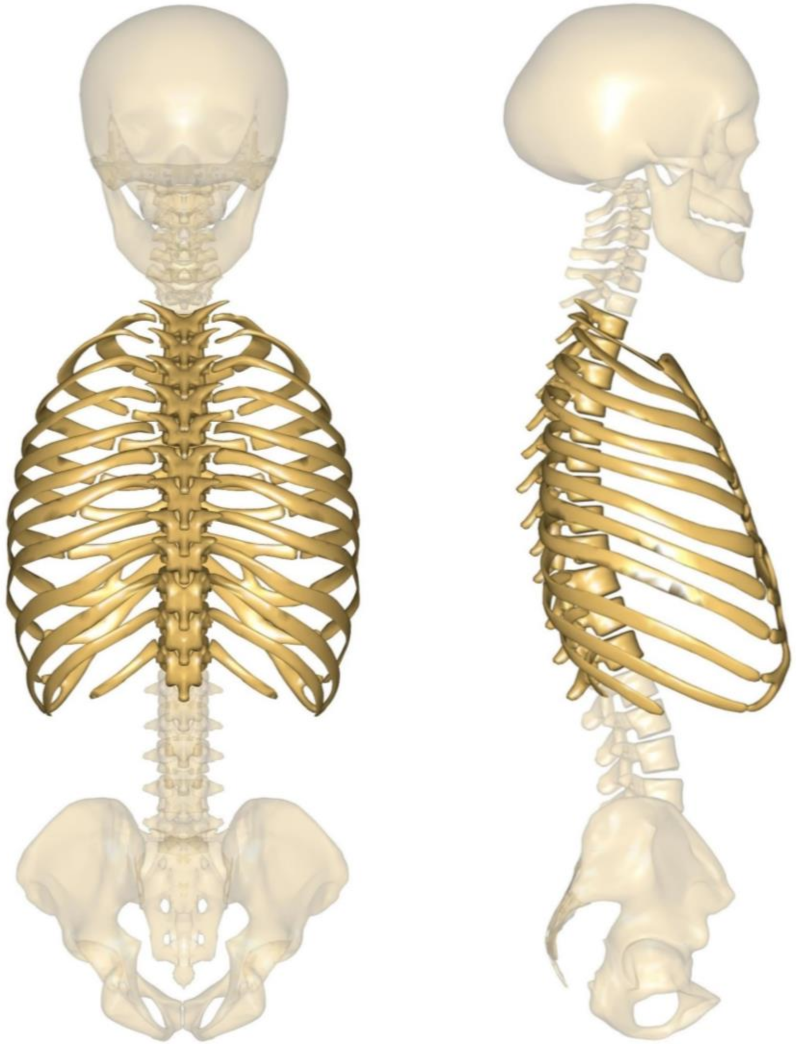
- **2,3,4,5**: Not published yet.

New thoracic spine and ribcage model

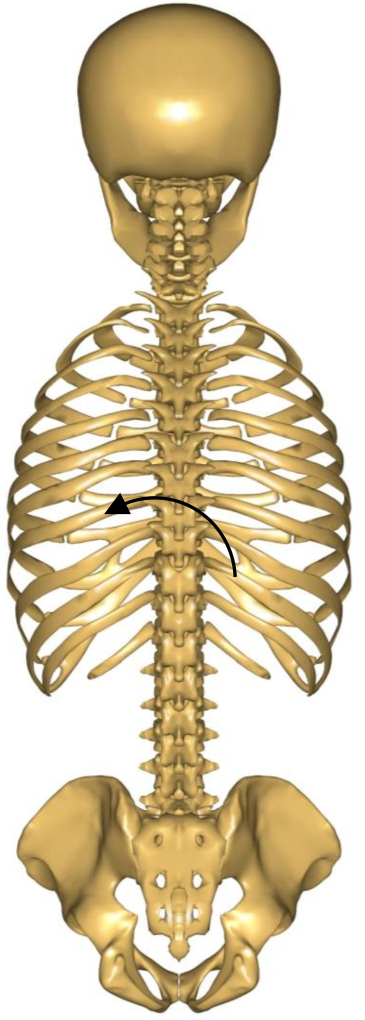
```
#define BM_TRUNK_THORACIC_MODEL   _THORACIC_MODEL_FLEXIBLE_
```

New bony segments:

- 12 thoracic vertebrae
- 24 ribs (left and right)
- 2 sternum segments



New thoracic spine and ribcage model



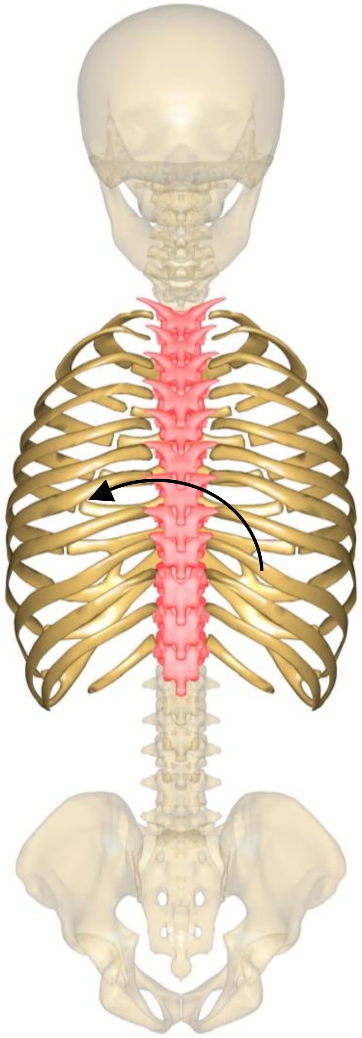
Ribcage is driven by newly defined averaging measure

Drive the spine

Features:

1. Determinate ribcage kinematics → No need for extra input drivers
2. Simulate detailed ribcage kinematics
3. Wide range of spine motion (robust)
4. Easy to use (MOCAP models)
5. Kinematically validated to:
   - Specimen’s rib movements
   - Scoliosis rib movements

Spine Drivers (model input)



Thoracic spine DoFs:
Spherical joints + 36 rotational DoFs (Input)

Input drivers

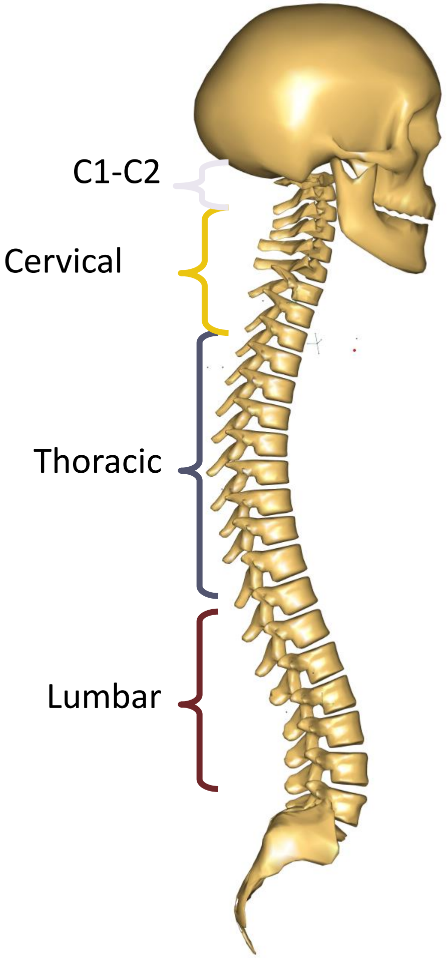
- Implemented rhythms (when no available data on all intervertebral angles)

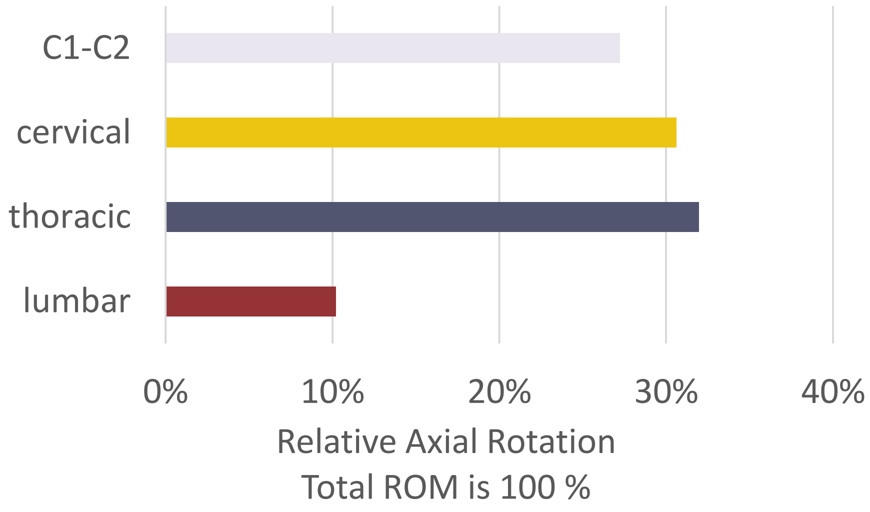
Or

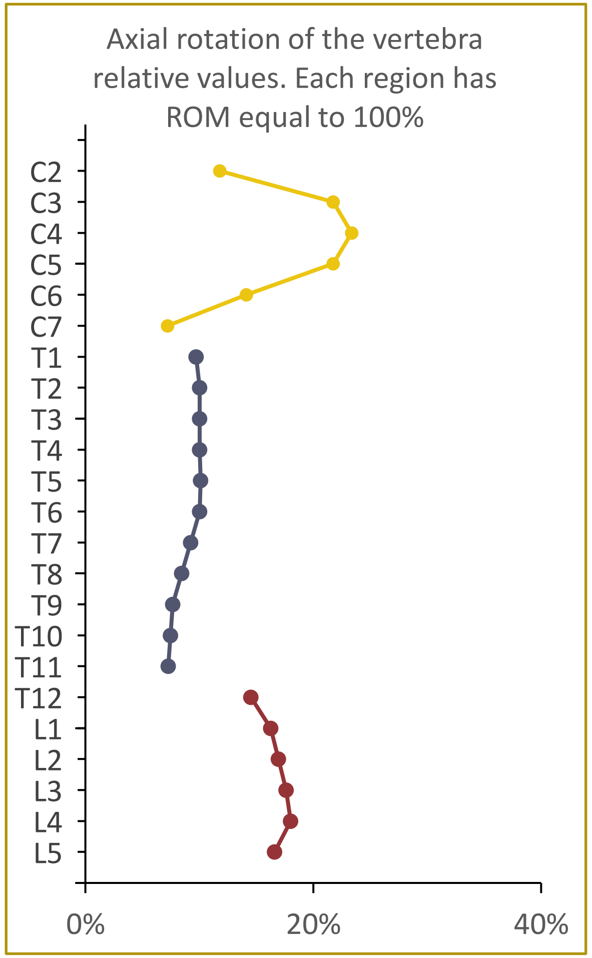
- Define 36 rotational drivers (Need to specify each intervertebral angle)

Spine Drivers: Implemented rhythms

- Explained in previous webcast by my colleague Morten Lund (Webcast: AMS 8)

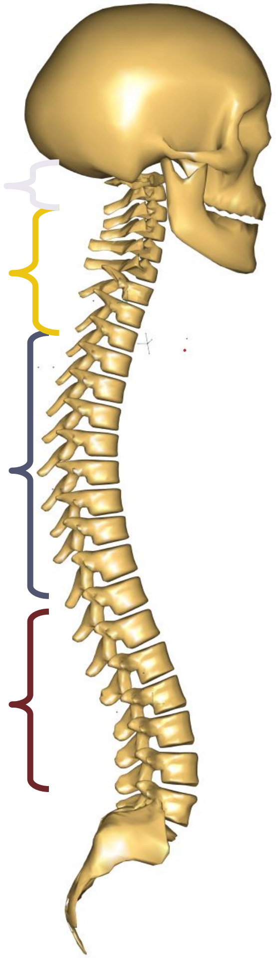






Spine Drivers: Implemented rhythms

- Explained in previous webcast by my colleague Morten Lund (Webcast: AMS 8)



Entire spine needs only 3 rotational drivers

```
 RhythmDriverLinear AxialRotationRhythmDriver(RELATIVE_TO_DOF=10, _REDEFINE_VARIABLES=On) =
    {
        AnyFloat RhythmCoefficients ??= {0.0727, 0.0747, 0.0766, 0.0845, 0.0923, 0.1002, 0.1012,
0.1002, 0.1002, 0.1002, 0.0972};

        Measures.Input = {
           AnyKinMeasure& T11T12_ref =.T11T12.Rotation;
           AnyKinMeasure& T10T11_ref =.T10T11.Rotation;
           AnyKinMeasure& T9T10_ref =.T9T10.Rotation;
           AnyKinMeasure& T8T9_ref =.T8T9.Rotation;
           AnyKinMeasure& T7T8_ref =.T7T8.Rotation;
           AnyKinMeasure& T6T7_ref =.T6T7.Rotation;
           AnyKinMeasure& T5T6_ref =.T5T6.Rotation;
           AnyKinMeasure& T4T5_ref =.T4T5.Rotation;
           AnyKinMeasure& T3T4_ref =.T3T4.Rotation;
           AnyKinMeasure& T2T3_ref =.T2T3.Rotation;
           AnyKinMeasure& T1T2_ref =.T1T2.Rotation;
        };
    };
```

Ribcage constraints

Determinate ribcage kinematics

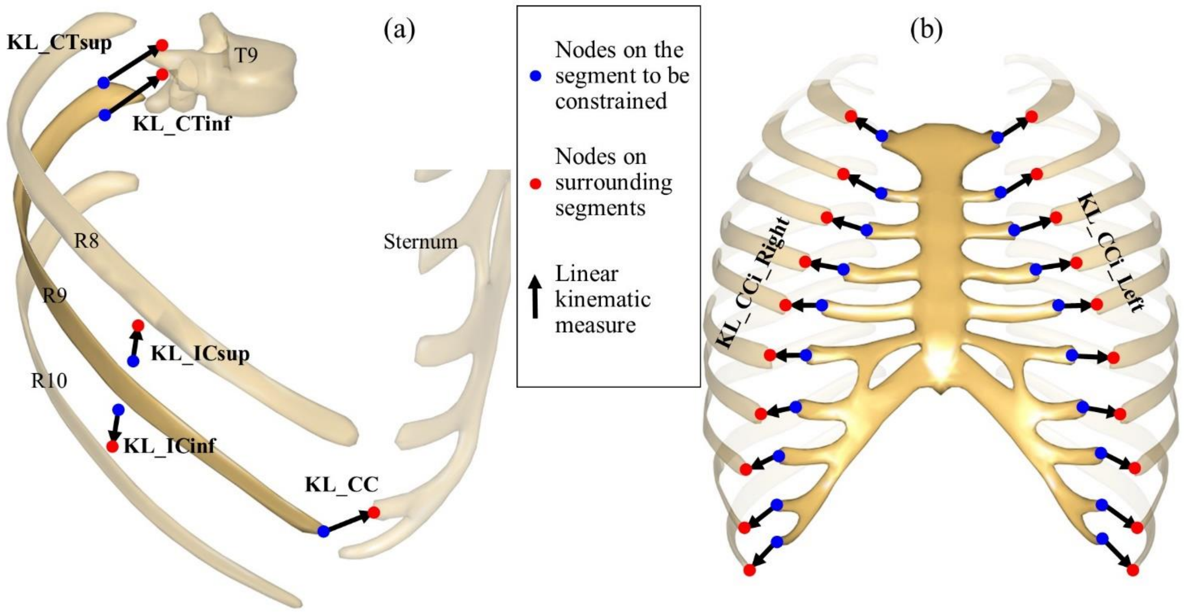
- **The complexity is due to multiple closed loops that forms the ribcage**
- Anatomical joint definition
- Replicate pathological deformities corresponding to clinical imaging

Ribcage constraints

Spherical joint in costovertebral joint node (connecting the ribs to vertebrae)

Averaging measure:

- Physically interpreted as the static equilibrium position between multiple linear springs (kinematics only).
- Constrain one segment to multiple others in an average sense (facilitates a kinematically determinate model with closed loops).
- Comprise three linear and three rotational sub-measures, which can be constrained.



New abdominal pressure model

```
#define BM_TRUNK_CAVITY_MODEL _CAVITY_MODEL_VOLUME_
```

Objects and features:

- 5 moving layers + pelvic layers
- 6 deformable volumes (New measure `AnyKinVolumeCylMesh`)
- Volumes can hold pressure, which can be transferred to adjacent objects
- Allow layer movements anteriorly (obesity)

Abdominal layers and volumes

Layer constraints:

- Spherical joints to relative vertebra (constrain three linear DoFs)
- Averaging constraints to find the layer position (constrain three rotational DoFs)

Abdominal layers and volumes

Segments and Constraints inside each layer:

- 4 segments connected with prismatic joints to each other
- Transfer the pressure through prismatic joints to adjacent layers and finally get balanced by muscles
- Can move anteriorly to simulate obesity

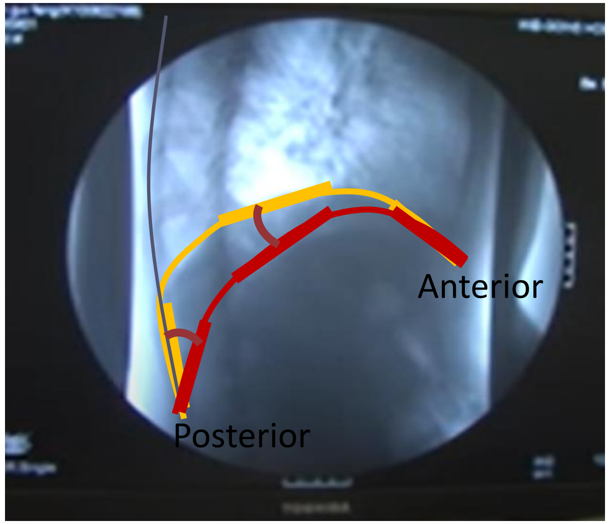
Diaphragm

Segments and Constraints:

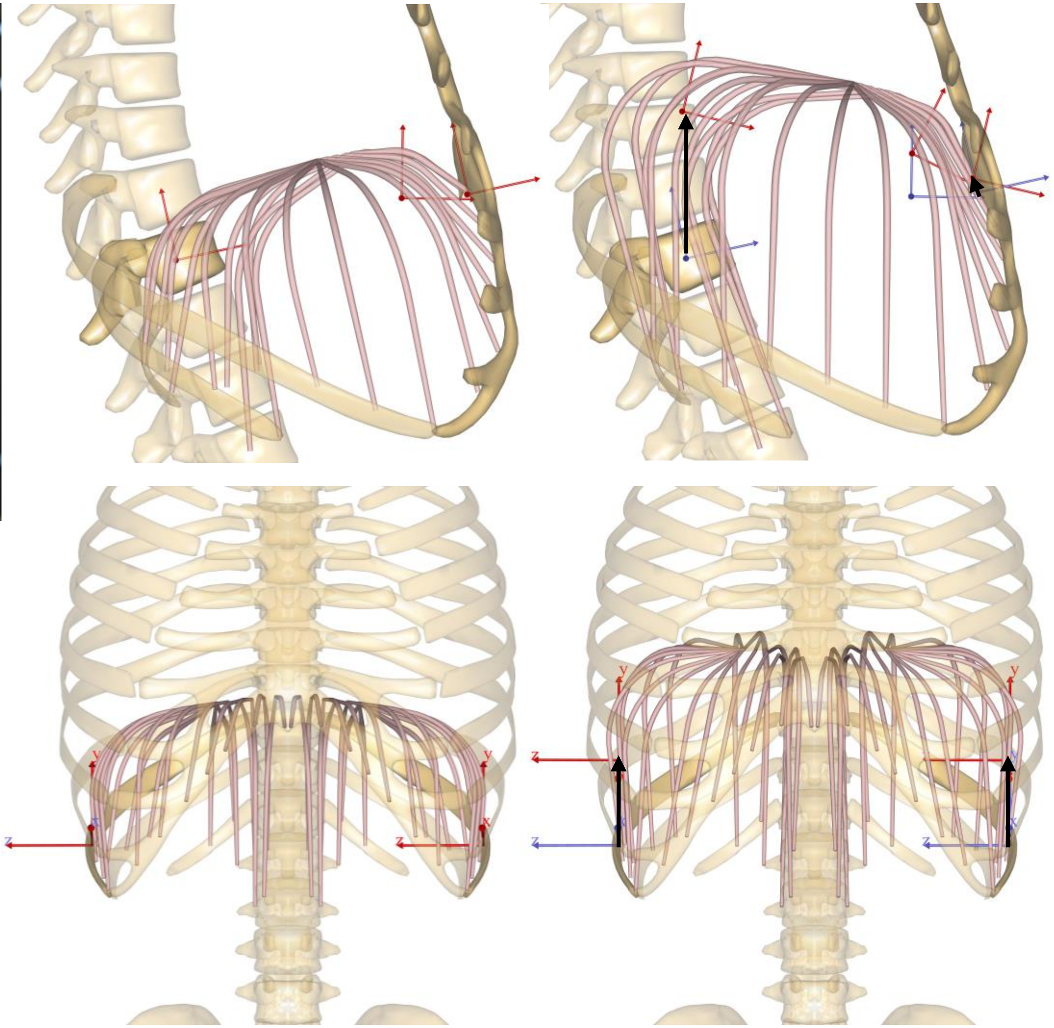
- Pressure is transferred to the top layer
- 4 segments, which constrained by surrounding ribs, sternum and vertebrae
- This mechanism allows to transfer the pressure through the volume to the top segments
- Diaphragm muscles balance the pressure force

Diaphragm

- Superoinferior diaphragm movement
- Diaphragm movement correspond to fluoroscopy movements
- Dome shape diaphragm with proper muscle wrapping
- Evenly distributed force on diaphragm muscles

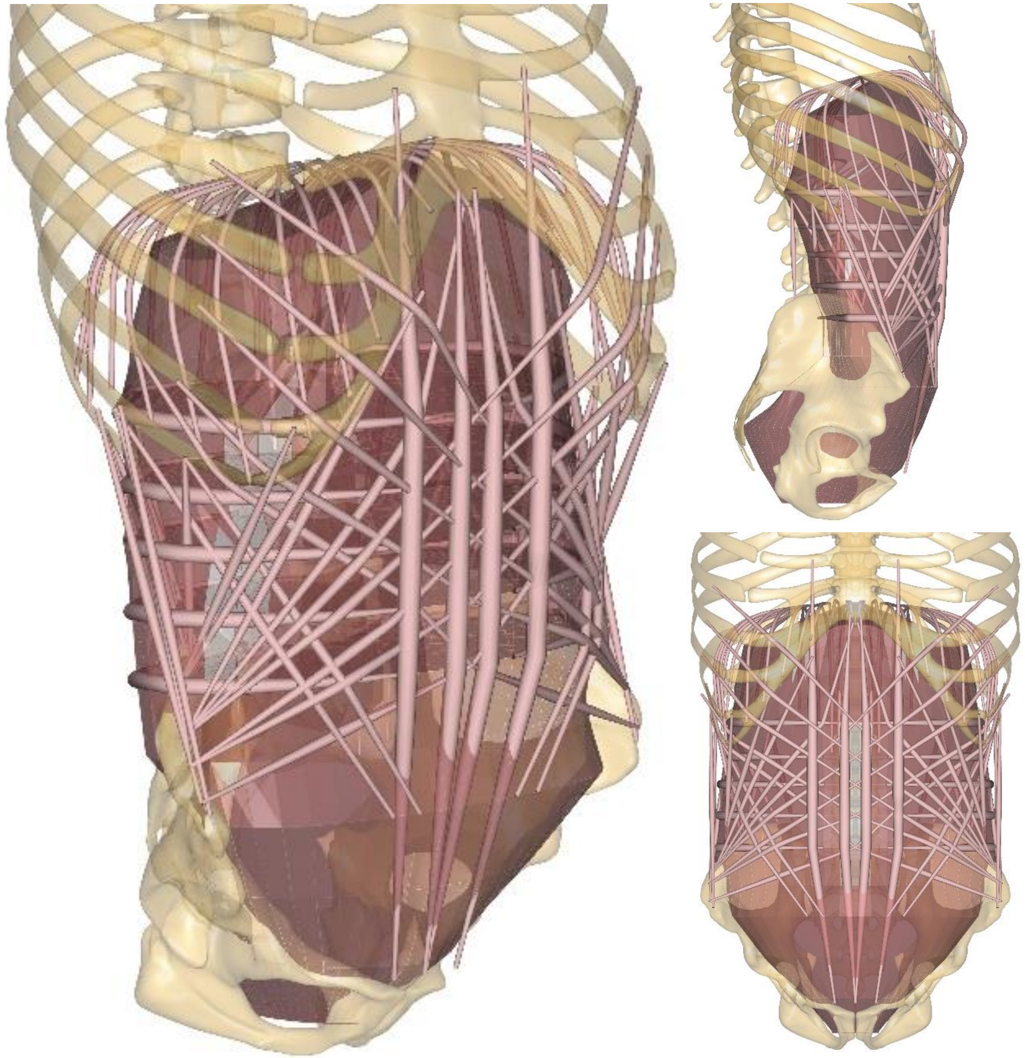


Red coordinates: nodes on the diaphragm.
Blue coordinates: nodes on surrounding segments

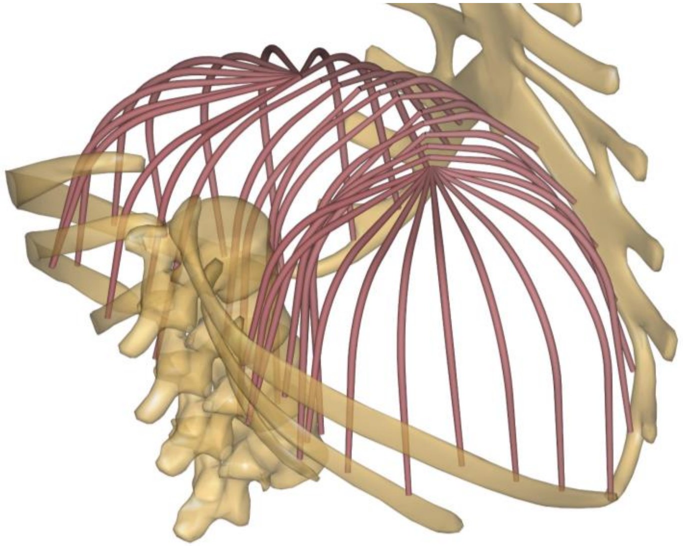


Abdomen mechanism

- **Pressure and volumes:**
  - Transfer pressure through the volumes (act as one volume)
- **Diaphragm muscles**:
  - Hold the pressure on the top end
  - Transfer the force to the ribcage
  - Result in an extensor moment to the ribcage.
- **Transversus, obliquus, and rectus muscles:**
  - Wrapped on layers
  - Apply force to the layers posteriorly
  - Create pressure (balance the pressure force).

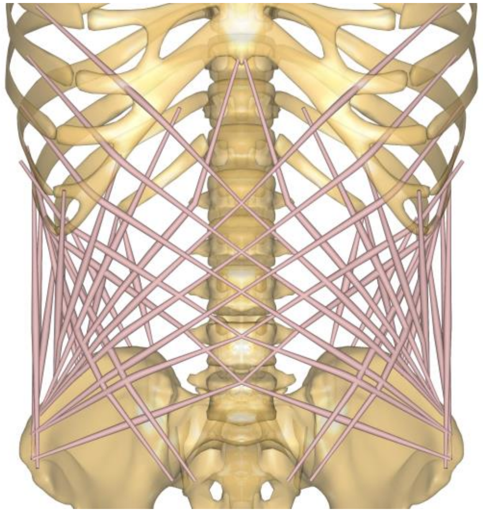


Detailed muscle configuration

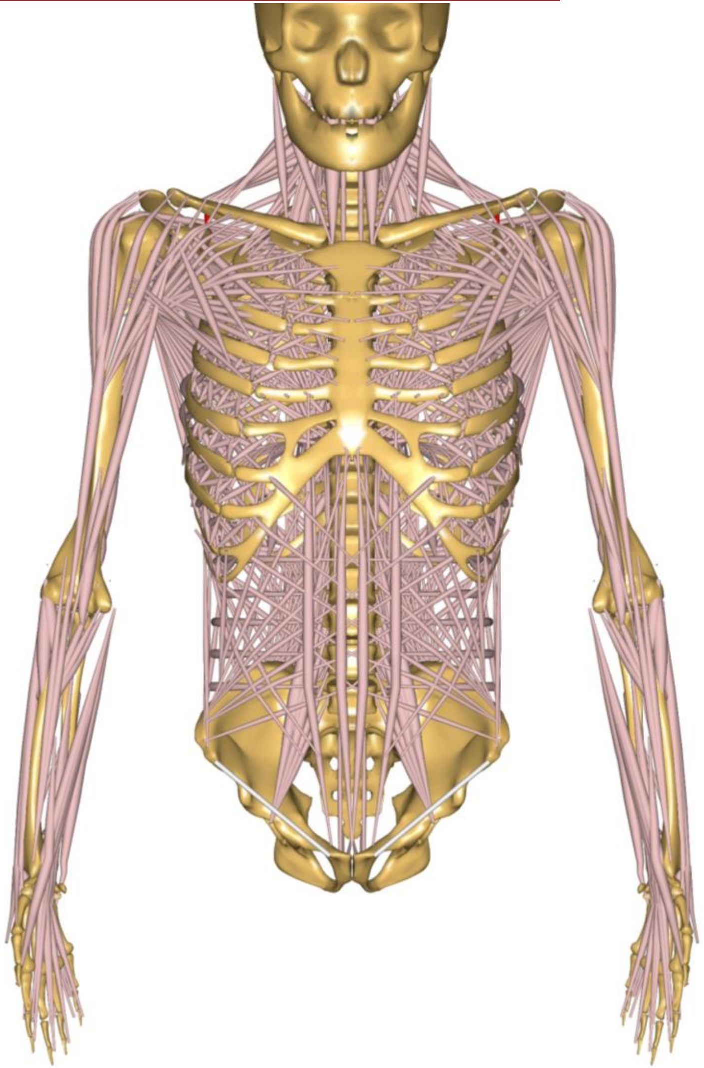


Diaphragm muscles

Obliquus muscles



Intercostalis muscles
(breathing)

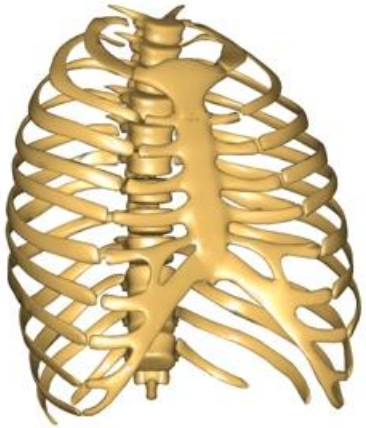


Few examples

Flexion-extension

Lateral bending

Axial rotation



Examples/ThoracicModel

```
// Add a driver which drives the whole spine.
// The spine rhythms handles the individual DOFs, but rhythms can be disabled
// for full control of all DOFs.
SimpleFourierDriver Trunk_Extension =
{
   AnyKinMeasure &ref1 = .BodyModel.Interface.Trunk.PelvisThoraxExtension;
   RangeOfMotion = {-35, 20}*pi/180;
};

SimpleFourierDriver Trunk_LateralBending =
{
   AnyKinMeasure &ref2 = .BodyModel.Interface.Trunk.PelvisThoraxLateralBending;
   RangeOfMotion = {-30, 30} *pi/180;
};
SimpleFourierDriver Trunk_AxialRotation =
{
   AnyKinMeasure &ref3 = .BodyModel.Interface.Trunk.PelvisThoraxRotation;
   RangeOfMotion = {-30,30} *pi/180;
};
```

Entire spine needs only 3 rotational drivers

Scoliosis model example

```
Main.Study.MechObjectExclude = {
      &Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvFlexion,
      &Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvRotation,
      &Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvLatBending,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.LateralBendingRhythmDriver,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.AxialRotationRhythmDriver,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.ExtensionRhythmDriver,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.LumbarThroacicExtensionLinkDriver,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.LumbarThroacicLatBendingLinkDriver,
      &Main.HumanModel.BodyModel.Trunk.Joints.Thorax.LumbarThroacicRotationLinkDriver
    };
```

OR

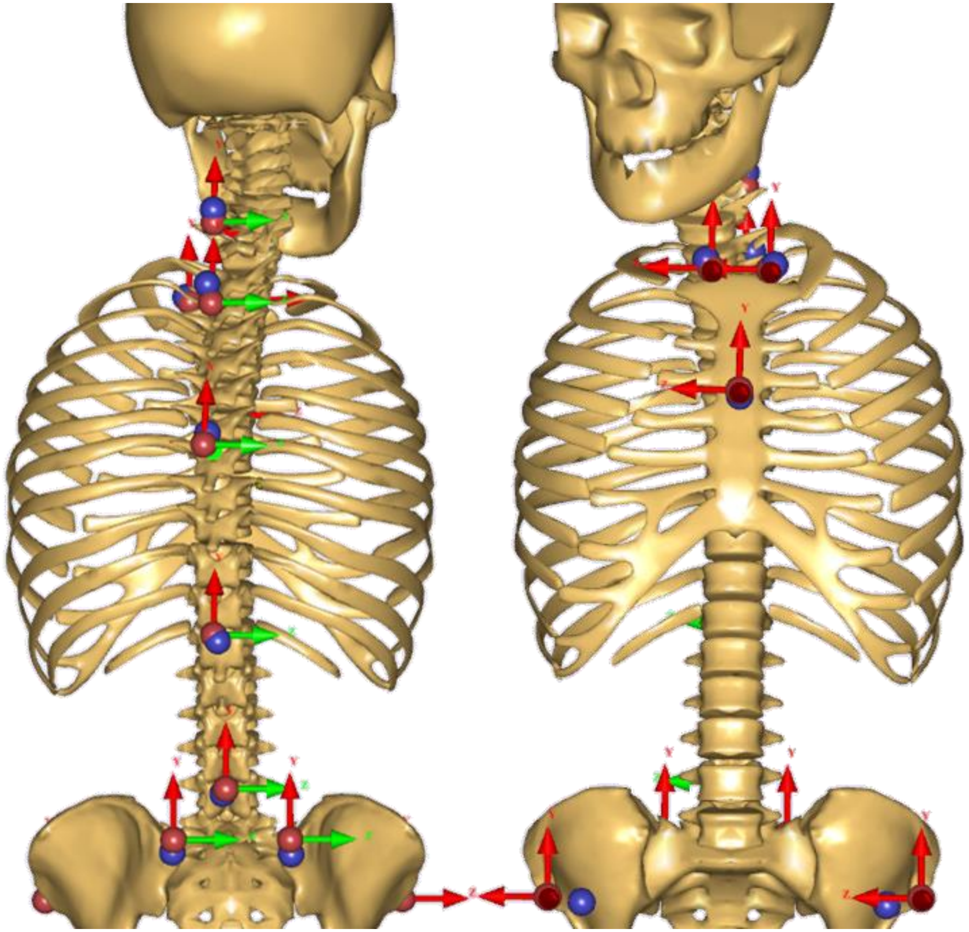
```
#define BM_TRUNK_LUMBAR_RHYTHM OFF
#define BM_TRUNK_THORACIC_RHYTHM OFF
```

```
AnyKinEqSimpleDriver spine_driver = {

      AnyKinMeasure& SacrumPelvis_ext = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.SacrumPelvis.Extension;
      AnyKinMeasure& L5Sacrum_ext = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.L5Sacrum.Extension;
      …..
      AnyKinMeasure& T2T3_ext = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T2T3.Extension;
      AnyKinMeasure& T1T2_ext = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T1T2.Extension;

      AnyKinMeasure& SacrumPelvis_rot = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.SacrumPelvis.Rotation;
      AnyKinMeasure& L5Sacrum_rot = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.L5Sacrum.Rotation;
      …..
      AnyKinMeasure& T2T3_rot = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T2T3.Rotation;
      AnyKinMeasure& T1T2_rot = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T1T2.Rotation;

      AnyKinMeasure& SacrumPelvis_lat = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.SacrumPelvis.LateralBending;
      AnyKinMeasure& L5Sacrum_lat = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.L5Sacrum.LateralBending;
      …..
      AnyKinMeasure& T2T3_lat = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T2T3.LateralBending;
      AnyKinMeasure& T1T2_lat = Main.HumanModel.BodyModel.Interface.Trunk.IntervertebralAngles.T1T2.LateralBending;
};
```

The ribcage and the abdominal layers will follow the spine alignment

Thoracic MOCAP model

```
#define BM_TRUNK_THORACIC_MODEL _THORACIC_MODEL_FLEXIBLE_
#define BM_TRUNK_LUMBAR_RHYTHM _RHYTHM_SOFT_
#define BM_TRUNK_THORACIC_RHYTHM _RHYTHM_SOFT_
#define BM_TRUNK_CERVICAL_RHYTHM _RHYTHM_SOFT_
#define USE_GRF_PREDICTION
#define SPINE_MARKERS_SINGLE

#ifdef SPINE_MARKERS_SINGLE
Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvRotation = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 1); }; };
  WeightFun =  {&Weight.Fun};
 };
 Main.HumanModel.BodyModel.Trunk.Joints.Thorax.AxialRotationRhythmDriver = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 1); }; };
  WeightFun =  {&Weight.Fun};
 };
  Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvLatBending = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 0.005); }; };
  WeightFun =  {&Weight.Fun};
 };
 Main.HumanModel.BodyModel.Trunk.Joints.Thorax.LateralBendingRhythmDriver = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 0.005); }; };
  WeightFun =  {&Weight.Fun};
 };
 Main.HumanModel.BodyModel.Trunk.Joints.Lumbar.SpineRhythmDrvFlexion = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 0.005); }; };
  WeightFun =  {&Weight.Fun};
 };
 Main.HumanModel.BodyModel.Trunk.Joints.Thorax.ExtensionRhythmDriver = {
  AnyFolder Weight = { AnyFunConst Fun ={ Value ??= repmat(..nDim, 0.005); }; };
  WeightFun =  {&Weight.Fun};
 };
```



Scoliosis MOCAP model

```
#define BM_TRUNK_THORACIC_MODEL _THORACIC_MODEL_FLEXIBLE_

#define BM_TRUNK_CERVICAL_RHYTHM _RHYTHM_SOFT_
#define BM_TRUNK_THORACIC_RHYTHM OFF
#define BM_TRUNK_LUMBAR_RHYTHM OFF
#define USE_GRF_PREDICTION
```

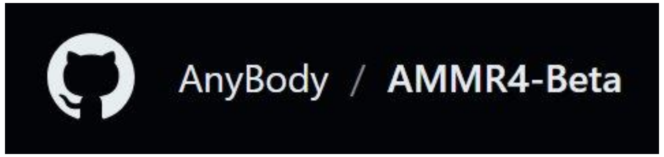
Need to define SCOLIOSIS_DRIVERS_SETUP (measure the angles from the Xray or similar data)

- Parameter identification with high weights
- Run analysis with low weights

Be more careful when adding the arms

Follow model development on Github

- Available on GitHub: https://github.com/anybody/ammr4-beta



Thank you for your attention

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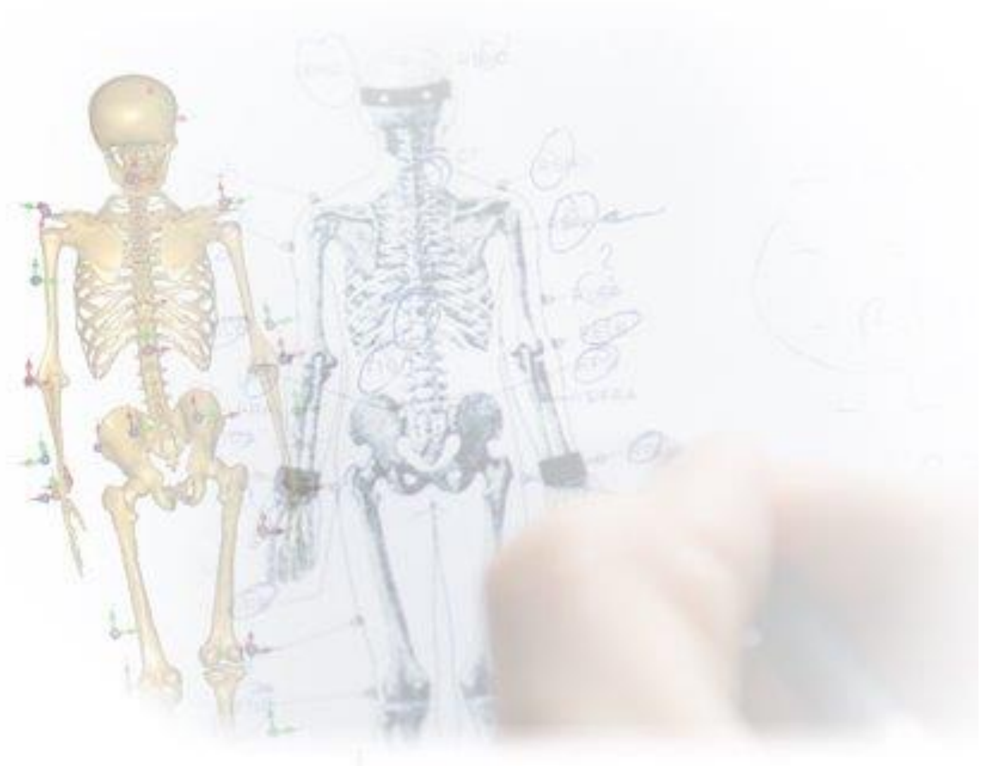

Q&A

?