

# Visual assessments of Postural Orientation Errors using ensembles of Deep Neural Networks



LTH  
FACULTY OF  
ENGINEERING

Master's Thesis

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# Agenda

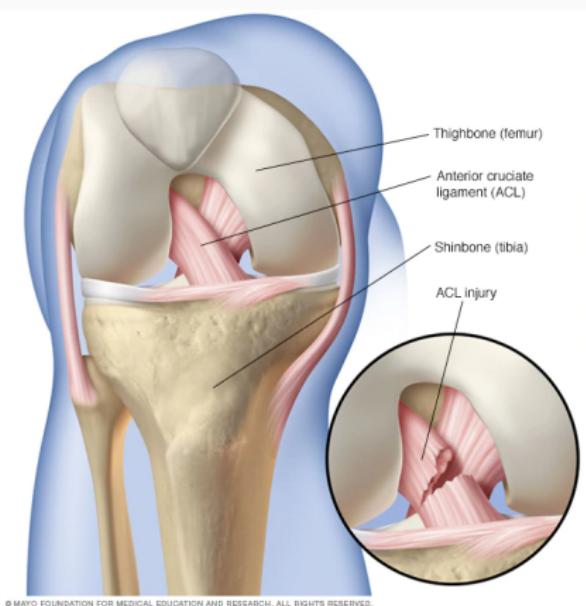
1. Introduction
2. Methods
3. Results
4. Conclusions and Future work

# Introduction

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# Anterior Cruciate Ligament injuries

- Around 8000 yearly Anterior cruciate ligament injuries in Sweden.
- Regular injury mechanism is sudden changes in direction or velocity while knee is bearing weight.
- Rehabilitation typically up to 2 years.
- Increased long and short term risk of, e.g., osteoarthritis, joint instability, and re-injury.



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Figure 1: Illustration of ACL in the knee<sup>1</sup>.

<sup>1</sup> Mayo Clinic, <https://www.mayoclinic.org/diseases-conditions/acl-injury/symptoms-causes/syc-20350738>

# Postural Orientation



Figure 2: Examples of maintained (left) and altered postural orientation (right) during a single leg squat.

- Ability to uphold alignment of body parts.
- Altered PO - seen to increase risk of re-injury.
- No established and feasible method to assess for clinical use.
- When used, found from motion capture systems.

# Postural Orientation Errors

- Proposed methods where experts assess motions from videos<sup>2</sup>.
- Scoring on ordinal scale, 0 (Good) - 2 (Poor).
- Patient score calculated as median of 4-5 repetition scores.
- Assessments are time consuming, can they be automated?
- Trunk, Pelvis, Femoral valgus, and KMFP POEs evaluated in this work for Single leg squat.

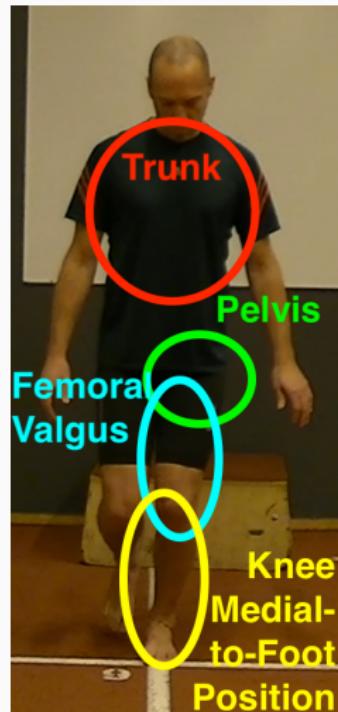


Figure 3: Evaluated POEs.

<sup>2</sup>Nae et al., Extended Version of a Test Battery for Visual Assessment of Postural Orientation Errors: Face Validity, Internal Consistency, and Reliability. 2020

## Methods

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# System overview

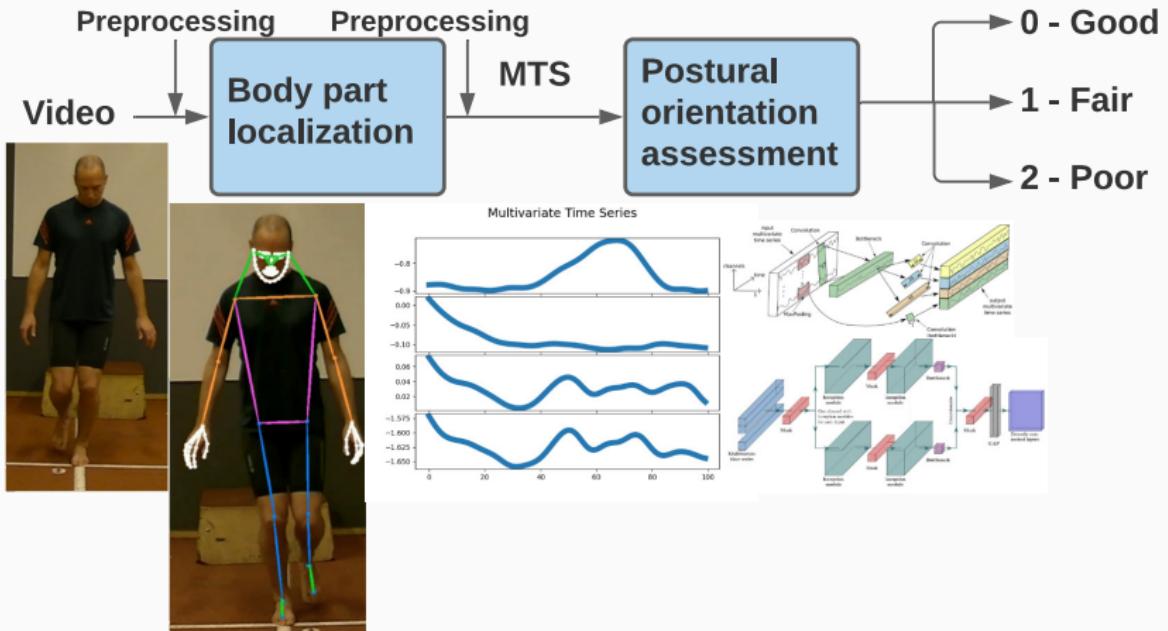


Figure 4: POE assessment system overview.

# Body part localization

- Built upon MMPose framework<sup>3</sup>.
- HRNet<sup>4</sup>with DARK-pose<sup>5</sup>trained on COCO-wholebody dataset used for pose estimation.
- Outputs 133 keypoint coordinates.

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<sup>3</sup>MMPose - OpenMMLab, <https://github.com/open-mmlab/mmpose>

<sup>4</sup>Sun et al., Deep high-resolution representation learning for human pose estimation. 2019

<sup>5</sup>Zhang et al., Distribution-Aware Coordinate Representation for Human Pose Estimation. 2020

# Time series classification - Network architectures

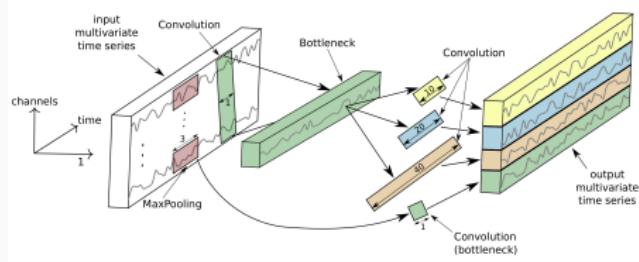


Figure 5: InceptionTime module<sup>6</sup>.

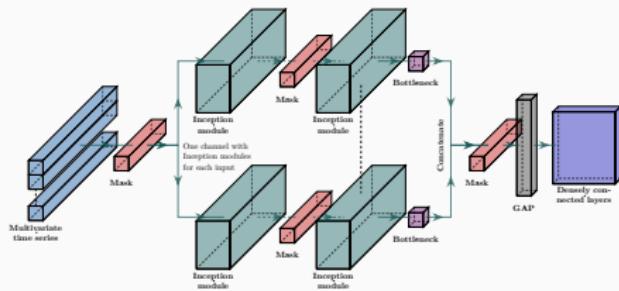


Figure 6: X-InceptionTime.

## InceptionTime<sup>6</sup>

Modules with convolutions of different lengths, global average pooling, and densely connected layers for classification.

## X-InceptionTime

Like InceptionTime, but input channels are kept separate.

<sup>6</sup>Fawaz et al., InceptionTime: Finding AlexNet for time series classification. 2020

# Inputs to classification

**Table 1:** Input variables for the different POEs. Videos have been mirrored such that action is performed with right leg, if applicable.

| Trunk              | Pelvis             | Femoral Valgus     | KMFP               |
|--------------------|--------------------|--------------------|--------------------|
| Left shoulder - x  | Right shoulder - x | Right shoulder - x | Left shoulder - y  |
| Right shoulder - x | Right shoulder - y | Right hip - x      | Right hip - y      |
| Right shoulder - y | Right hip - x      | Right knee - y     | Angle: right       |
| Left hip - x       | Right hip - y      | Angle: right       | ankle and toes     |
| Left hip - y       | Left hip - y       | knee and ankle     | Difference: right  |
| Right hip - x      | Difference: right  |                    | hip and knee - x   |
| Difference: right  | hip and knee - x   |                    | Difference: right  |
| hip and knee - x   | Difference: right  |                    | knee and ankle - x |
|                    | knee and toes - x  |                    |                    |

# Time series classification - Ensembles

- Each classification is obtained from ensembles of 5 classifier models.
- 2 models perform well over all classes - CORAL<sup>7</sup>ordinal classifiers.
- Remaining models optimized for low false positive rates for one class each - class weights or modified cross-entropy loss.

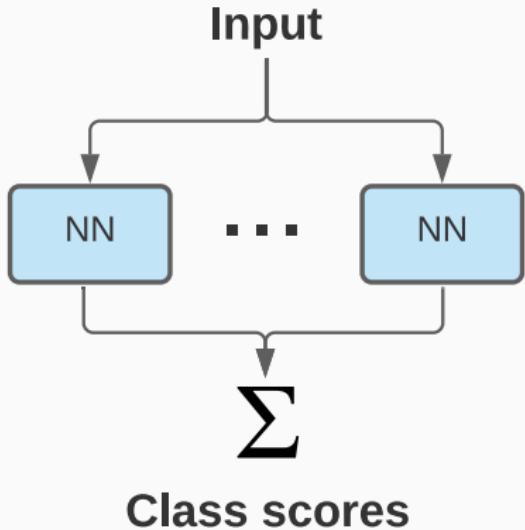


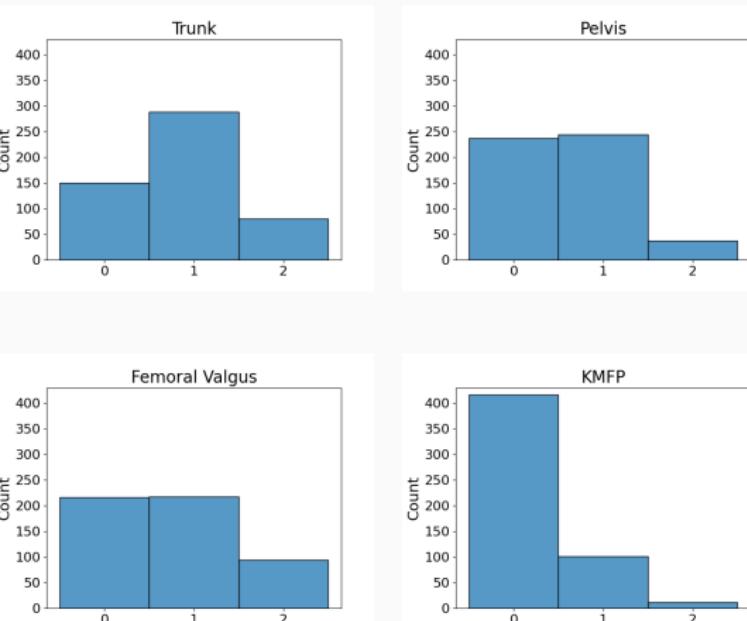
Figure 7: Ensemble structure used for classification.

<sup>7</sup>Cao et al., Rank consistent ordinal regression for neural networks with application to age estimation. 2019

## Results

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# Data

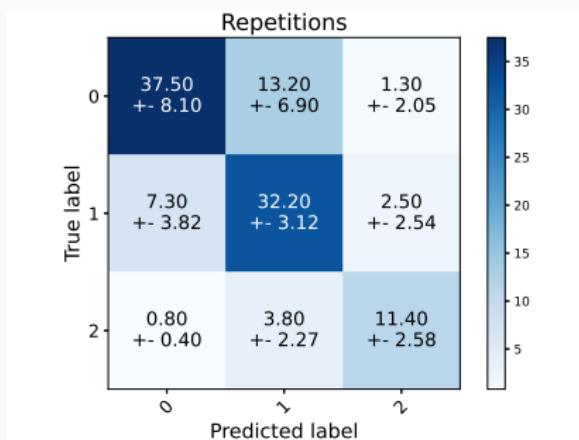


**Figure 8:** Class distributions for the different POEs.

- Videos with 4-5 repetitions.
- 103 unique subjects.
- Assessments for right and left leg for some subjects/POEs - 105-107 assessed videos, 519-530 repetitions.
- 20% (22 unique subjects, 110 repetitions) test set.
- 10-fold cross-validation used. Results shown are mean ( $\pm$  std) of the 10 resulting models on test set.

# Trunk

Accuracy (%):  $73.7 \pm 4.5$



$75.0 \pm 7.9$

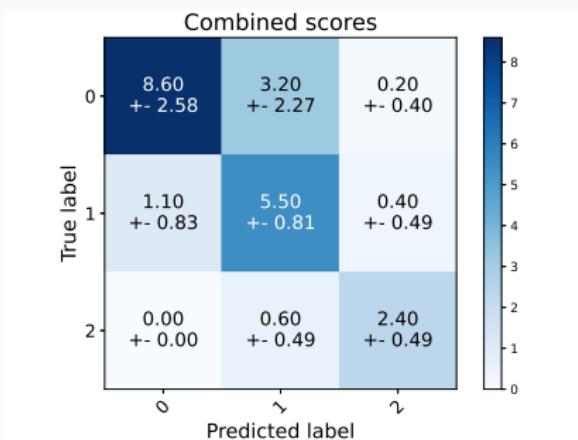
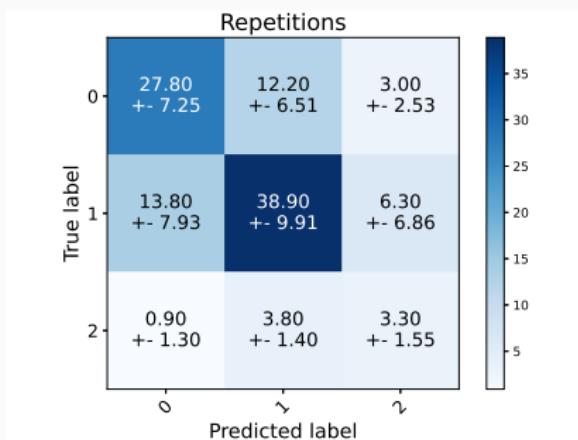


Figure 9: Confusion matrices for the classification of the repetitions (left) and the combined scores (right).

# Pelvis

Accuracy (%):  $63.6 \pm 10.7$



$69.1 \pm 10.1$

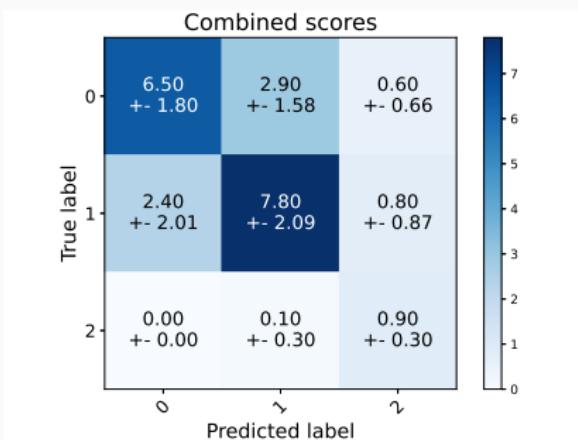
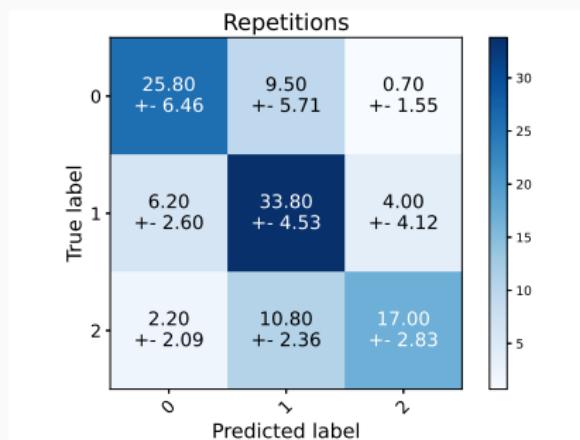


Figure 10: Confusion matrices for the classification of the repetitions (left) and the combined scores (right).

# Femoral Valgus

Accuracy (%):  $69.6 \pm 6.8$



$79.1 \pm 9.3$

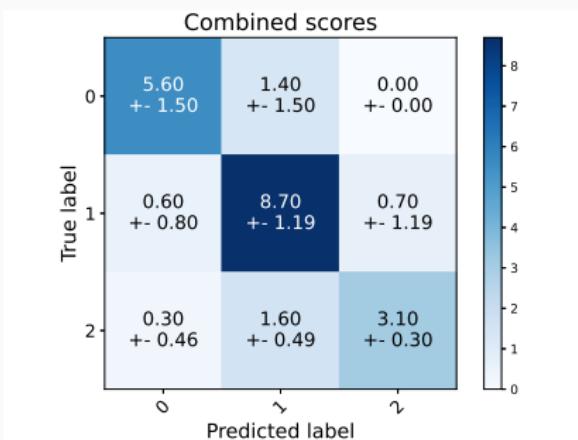
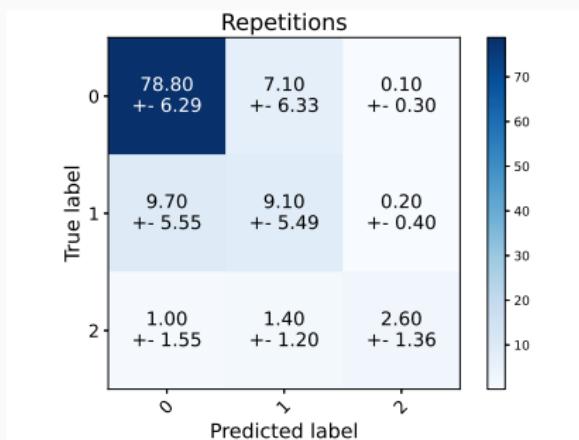


Figure 11: Confusion matrices for the classification of the repetitions (left) and the combined scores (right).

# Knee Medial-to-Foot Position

Accuracy (%):  $82.3 \pm 3.1$



$89.5 \pm 4.5$

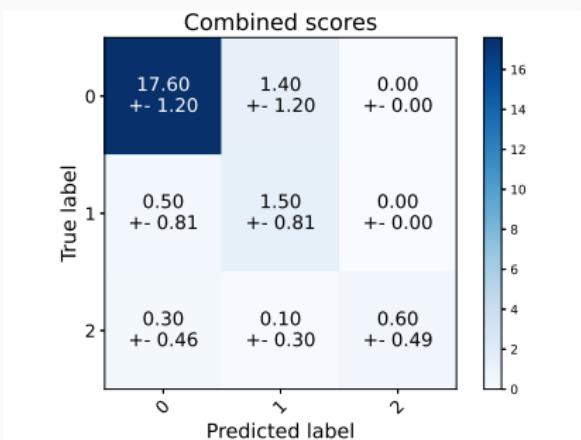


Figure 12: Confusion matrices for the classification of the repetitions (left) and the combined scores (right).

## Summary

**Table 2:** Summary of results, here the combined scores with thresholds removing samples the models are uncertain about.

|                      | Trunk          | Pelvis          | Femoral Valgus | KMFP            |
|----------------------|----------------|-----------------|----------------|-----------------|
| <b>Accuracy (%)</b>  | $80.0 \pm 7.8$ | $73.3 \pm 18.9$ | $82.3 \pm 6.0$ | $90.3 \pm 4.3$  |
| <b>F1 score (%)</b>  | $79.9 \pm 8.9$ | $73.6 \pm 22.3$ | $81.0 \pm 5.2$ | $74.0 \pm 22.3$ |
| <b>Recall (%)</b>    | $81.6 \pm 7.2$ | $77.9 \pm 14.9$ | $79.5 \pm 5.5$ | $81.1 \pm 24.7$ |
| <b>Precision (%)</b> | $83.0 \pm 6.8$ | $74.9 \pm 23.8$ | $86.5 \pm 5.6$ | $71.4 \pm 22.6$ |

## **Conclusions and Future work**

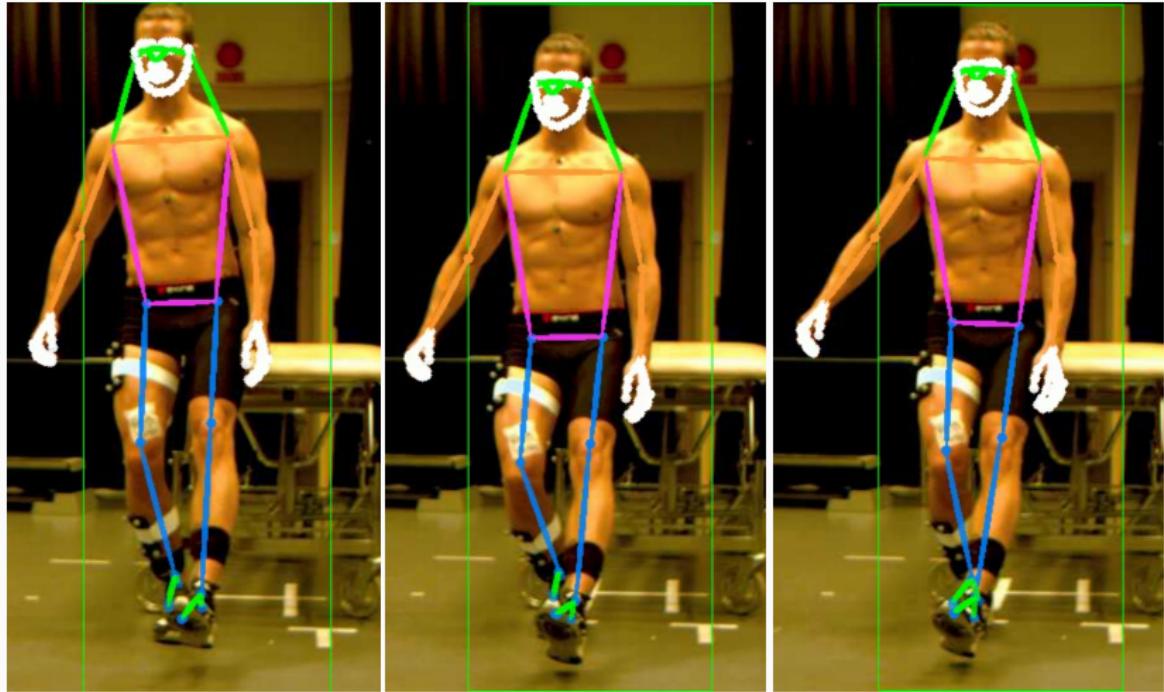
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## Conclusions and Future work

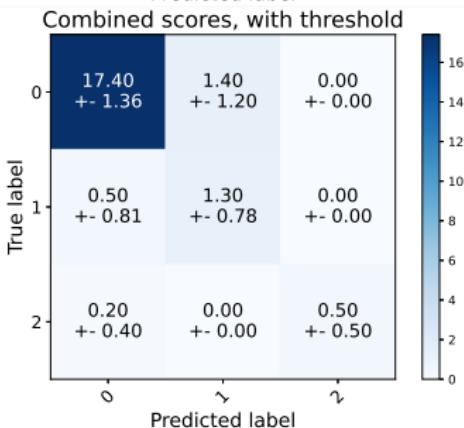
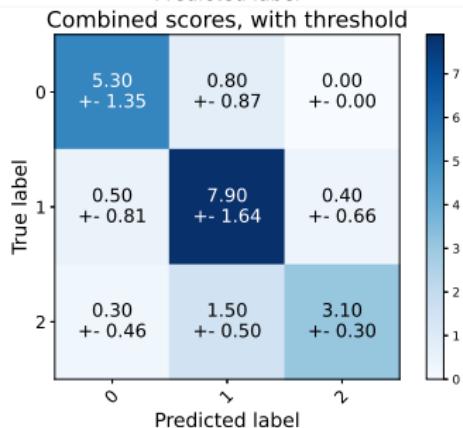
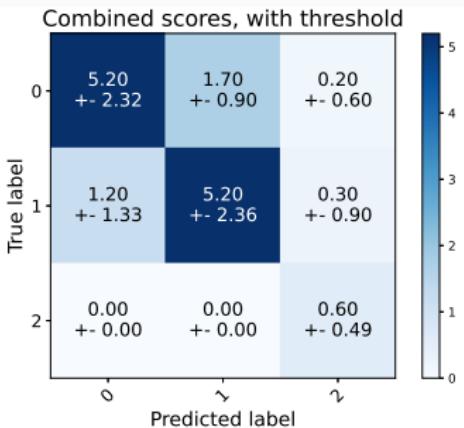
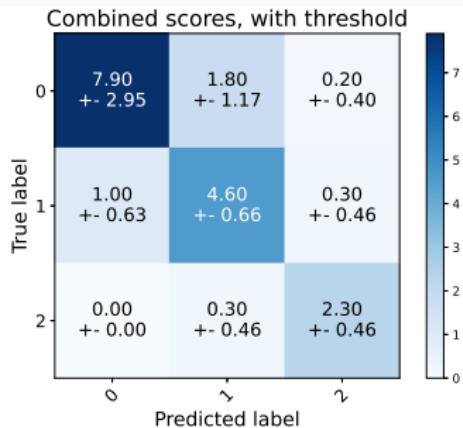
- The results suggests the proposed method could automate assessments.
- Large variance in results suggests more data needed.
- Future work:
  - Label videos differently.
  - Evaluate 3D coordinate reconstruction.
  - Non-uniform weighting in ensembles and when combining scores.
  - Assess more POEs and motions.

**Thank you**

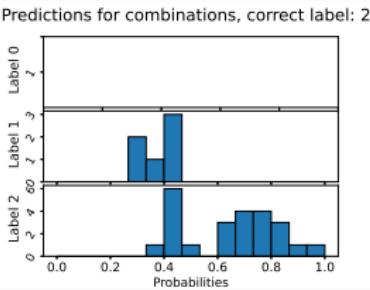
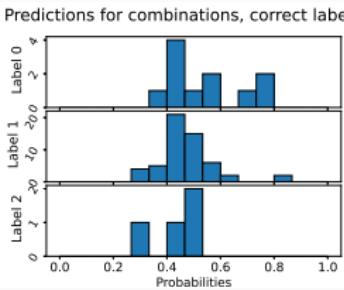
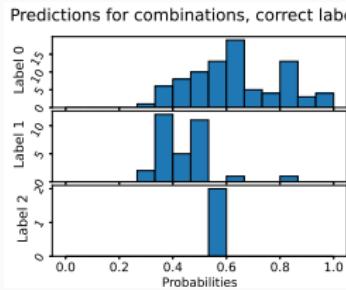
## Occluded body parts



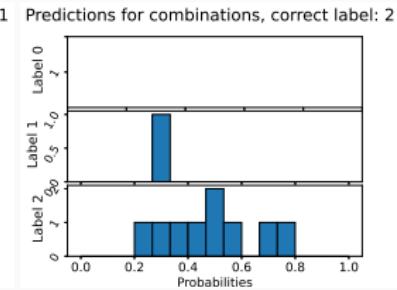
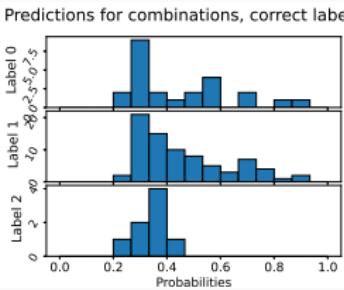
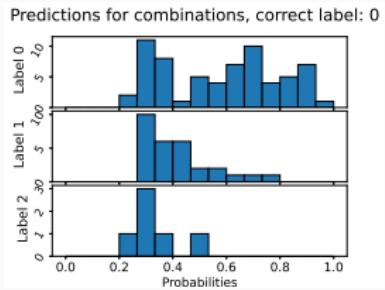
# Confusion matrices for patient scores with thresholds



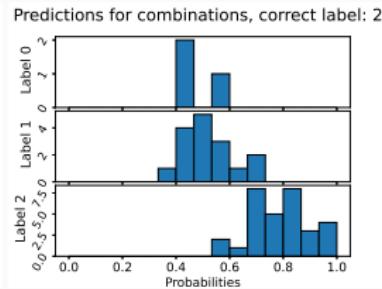
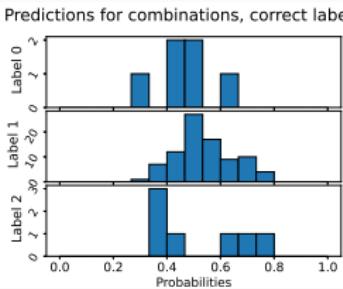
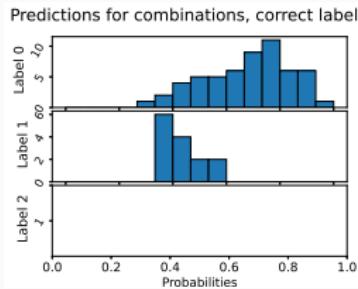
# Ensemble's confidence in predicted classes - Trunk



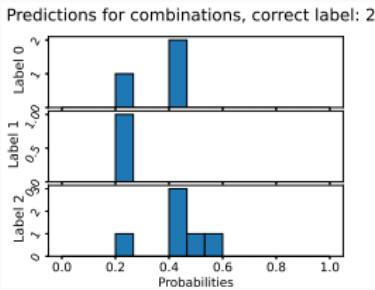
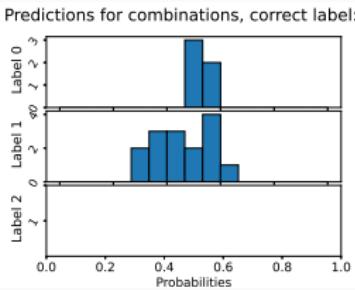
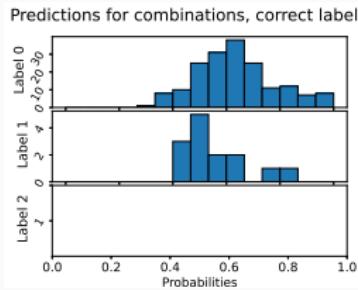
# Ensemble's confidence in predicted classes - Pelvis



# Ensemble's confidence in predicted classes - Femoral Valgus



# Ensemble's confidence in predicted classes - KMFP



# Descriptions for the visual assessments

| Segment-specific POEs                   | Scoring of 0:<br>Good (no POE)  | Scoring of 1:<br>Fair (minor POE)  | Scoring of 2:<br>Poor (major POE)   |
|---|---|--|---|
| <b>Deviation of trunk in any plane</b>  | The absence of a trunk position into forward lean, lateral lean and/or rotation indicates no POE                  | A slight position of the trunk into forward lean, lateral lean and/or rotation indicates minor POE                             | A clear position of the trunk into forward lean, lateral lean and/or rotation indicates major POE                             |
| <b>Deviation of pelvis in any plane</b> | The absence of pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates no POE | A slight position of the pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates minor POE | A clear position of the pelvis into lateral deviation, pelvic tilt and/or rotation of pelvis respectively indicates major POE |
| <b>Femoral valgus</b>                   | The absence of femoral valgus indicates no POE  | A slight position of femoral valgus indicates minor POE  | A clear position of femoral valgus indicates major POE  |
| <b>Knee Medial-to-Foot Position</b>     | Mid-point of patella is in line with or lateral to the second toe   | Mid-point of patella is placed medial to the second toe  | Mid-point of patella is clearly placed medial to the big toe  |

## Loss functions

**CORAL:**

$$\mathcal{L}(\mathbf{x}, \mathbf{W}, \mathbf{b}) = - \sum_{n=1}^N \sum_{k=1}^{K-1} \lambda^{(k)} [\log(\sigma(g(\mathbf{x}_n, \mathbf{W}) + b_k))y_n^{(k)} + \log(1 - \sigma(g(\mathbf{x}_n, \mathbf{W}) + b_k))(1 - y_n^{(k)})] \quad (1)$$

**Confusion-entropy:**

$$\mathcal{L}(\mathbf{x}, \mathbf{W}, U) = - \sum_{i=1}^K \sum_{j=1}^K u_{ij} \log \sum_{n=1}^N y_n^{(i)} \hat{y}_n^{(j)}(\mathbf{x}_n, \mathbf{W}) \quad (2)$$

with  $U$ , e.g.,  $\begin{bmatrix} 0.6 & 0.05 & 0.05 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$

## Data available for the different POEs

| POE            | Number of unique subjects | Number of repetition sequences | Number of repetitions |
|----------------|---------------------------|--------------------------------|-----------------------|
| Trunk          | 103                       | 105                            | 520                   |
| Pelvis         | 103                       | 105                            | 519                   |
| Femoral Valgus | 103                       | 107                            | 530                   |
| KMFP           | 103                       | 107                            | 530                   |

## Detailed results - Trunk

|               | Rep.           | Comb.          | Thresh.                          | Certainties                      |                 |                 |
|---------------|----------------|----------------|----------------------------------|----------------------------------|-----------------|-----------------|
|               |                |                |                                  | 1( $n=15$ )                      | 2( $n=6$ )      | 3( $n=1$ )      |
| Accuracy (%)  | $73.7 \pm 4.5$ | $75.0 \pm 7.9$ | <b><math>80.0 \pm 7.8</math></b> | <b><math>81.3 \pm 7.1</math></b> | $56.7 \pm 15.2$ | $90.0 \pm 30.0$ |
| F1 score (%)  | $73.1 \pm 3.4$ | $75.0 \pm 5.8$ | <b><math>79.9 \pm 8.9</math></b> | <b><math>80.4 \pm 7.1</math></b> | $25.8 \pm 6.3$  | $90.0 \pm 30.0$ |
| Recall (%)    | $73.3 \pm 3.7$ | $76.7 \pm 3.8$ | <b><math>81.6 \pm 7.2</math></b> | <b><math>81.1 \pm 5.0</math></b> | $28.0 \pm 11.0$ | $30.0 \pm 10.0$ |
| Precision (%) | $76.7 \pm 4.1$ | $78.7 \pm 5.2$ | <b><math>83.0 \pm 6.8</math></b> | <b><math>84.9 \pm 5.9</math></b> | $28.9 \pm 6.8$  | $30.0 \pm 10.0$ |

## Detailed results - Pelvis

|               | Rep.            | Comb.           | Thresh.                           | Certainties     |                                   |                 |
|---------------|-----------------|-----------------|-----------------------------------|-----------------|-----------------------------------|-----------------|
|               |                 |                 |                                   | 1( $n=14$ )     | 2( $n=7$ )                        | 3( $n=1$ )      |
| Accuracy (%)  | $63.6 \pm 10.7$ | $69.1 \pm 10.1$ | <b><math>73.3 \pm 18.9</math></b> | $67.9 \pm 15.0$ | <b><math>70.0 \pm 19.6</math></b> | $80.0 \pm 40.0$ |
| F1 score (%)  | $55.7 \pm 13.4$ | $66.5 \pm 15.0$ | <b><math>73.6 \pm 22.3</math></b> | $58.0 \pm 20.1$ | <b><math>63.7 \pm 23.8</math></b> | $31.7 \pm 17.4$ |
| Recall (%)    | $57.3 \pm 12.0$ | $75.3 \pm 14.0$ | <b><math>77.9 \pm 14.9</math></b> | $56.8 \pm 20.7$ | <b><math>64.6 \pm 22.8</math></b> | $31.7 \pm 17.4$ |
| Precision (%) | $58.3 \pm 14.9$ | $67.0 \pm 14.4$ | <b><math>74.9 \pm 23.8</math></b> | $62.5 \pm 19.7$ | <b><math>68.4 \pm 24.0</math></b> | $31.7 \pm 17.4$ |

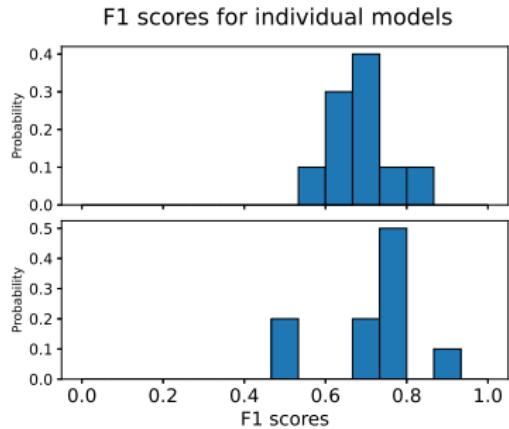
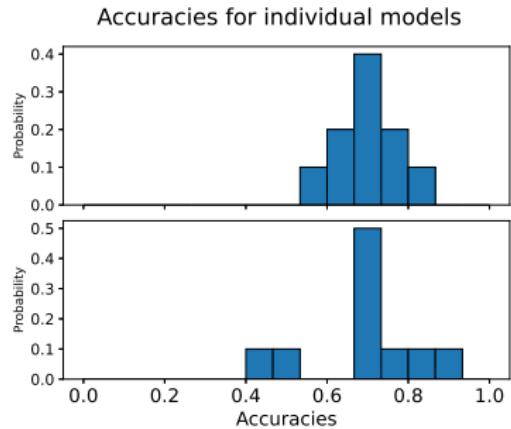
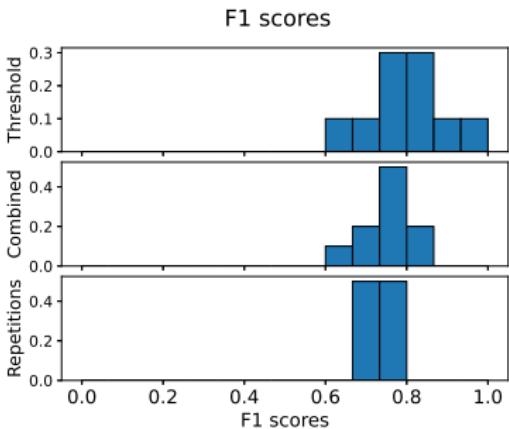
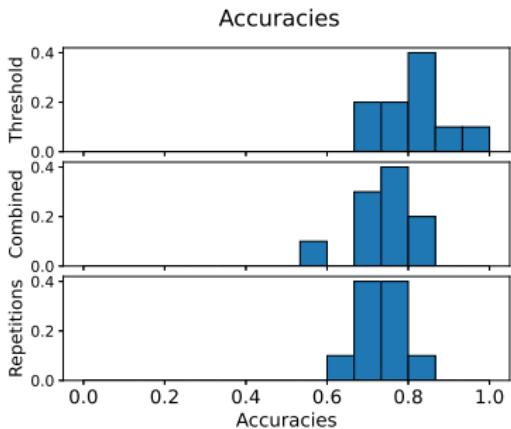
# Detailed results - Femoral Valgus

|               | Rep.           | Comb.          | Thresh.        | Certainties    |                 |            |
|---------------|----------------|----------------|----------------|----------------|-----------------|------------|
|               |                |                |                | 1( $n=15$ )    | 2( $n=7$ )      | 3( $n=0$ ) |
| Accuracy (%)  | $69.6 \pm 6.8$ | $79.1 \pm 9.3$ | $82.3 \pm 6.0$ | $82.7 \pm 9.5$ | $71.4 \pm 11.0$ | -          |
| F1 score (%)  | $69.0 \pm 6.6$ | $77.6 \pm 8.6$ | $81.0 \pm 5.2$ | $80.8 \pm 8.6$ | $70.1 \pm 9.4$  | -          |
| Recall (%)    | $68.4 \pm 6.3$ | $76.3 \pm 8.1$ | $79.5 \pm 5.5$ | $80.4 \pm 7.4$ | $71.1 \pm 9.5$  | -          |
| Precision (%) | $74.0 \pm 7.4$ | $83.8 \pm 7.4$ | $86.5 \pm 5.6$ | $85.2 \pm 7.6$ | $81.8 \pm 6.6$  | -          |

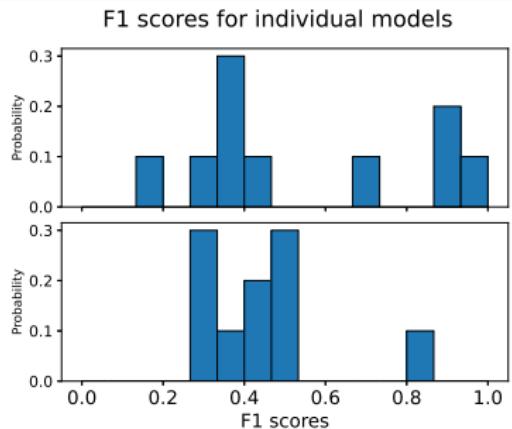
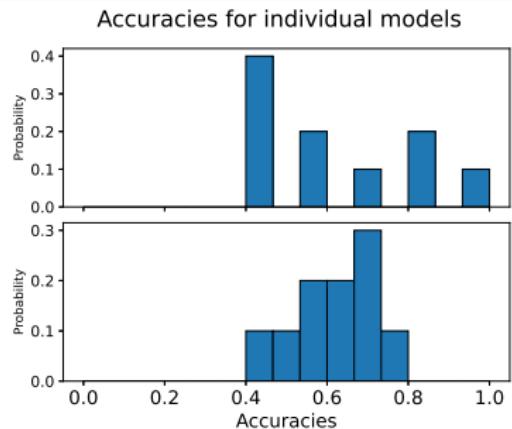
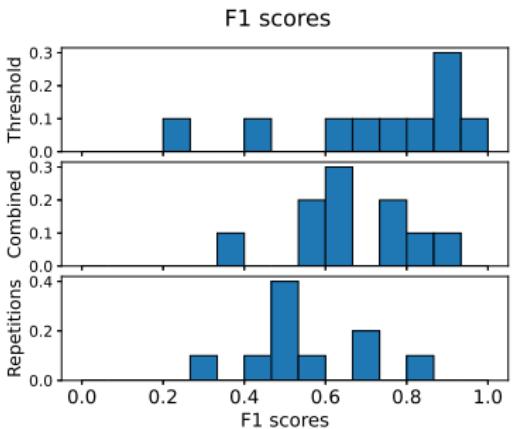
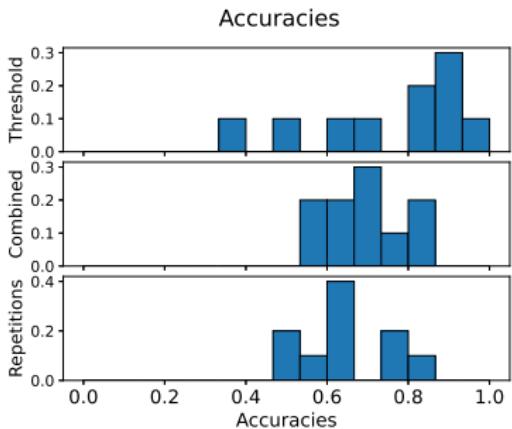
# Detailed results - KMFP

|               | Rep.            | Comb.           | Thresh.         | Certainties     |                 |                 |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|               |                 |                 |                 | 1( $n=19$ )     | 2( $n=2$ )      | 3( $n=1$ )      |
| Accuracy (%)  | $82.3 \pm 3.1$  | $89.5 \pm 4.5$  | $90.3 \pm 4.3$  | $92.6 \pm 5.3$  | $90.0 \pm 20.0$ | $30.0 \pm 45.8$ |
| F1 score (%)  | $65.1 \pm 13.7$ | $69.0 \pm 24.6$ | $74.0 \pm 22.3$ | $69.3 \pm 28.6$ | $57.8 \pm 17.8$ | $10.0 \pm 15.3$ |
| Recall (%)    | $63.8 \pm 14.4$ | $75.9 \pm 26.7$ | $81.1 \pm 24.7$ | $75.3 \pm 29.4$ | $60.0 \pm 13.3$ | $10.0 \pm 15.3$ |
| Precision (%) | $78.5 \pm 8.2$  | $66.1 \pm 24.0$ | $71.4 \pm 22.6$ | $67.2 \pm 28.9$ | $56.7 \pm 20.0$ | $10.0 \pm 15.2$ |

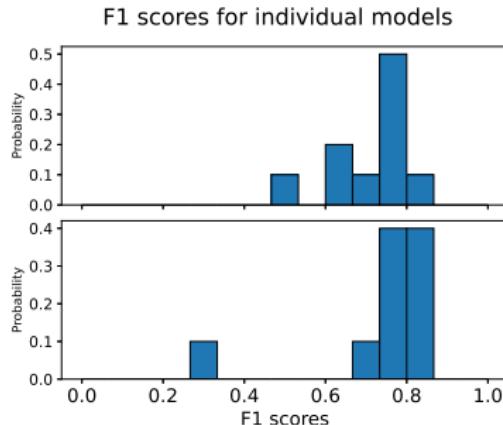
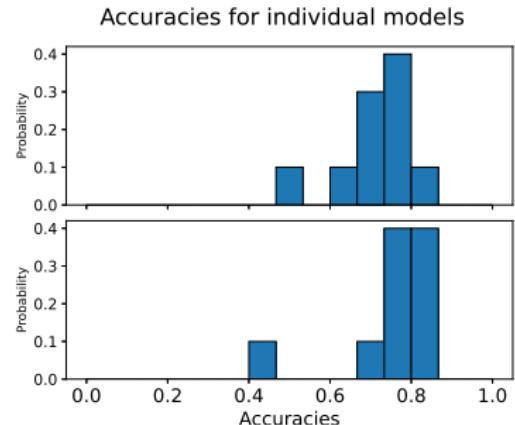
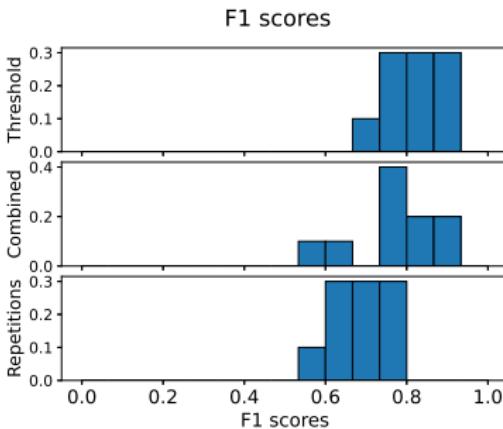
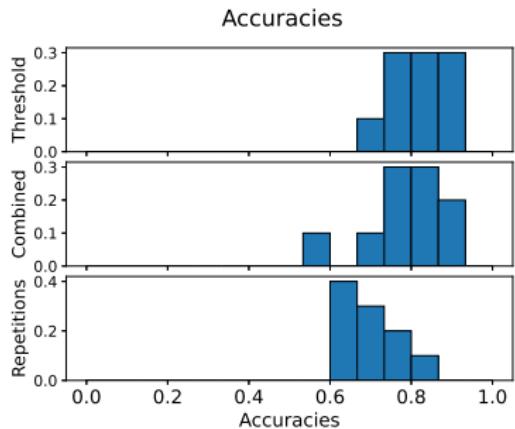
# Histograms over accuracies and F1 scores - Trunk



# Histograms over accuracies and F1 scores - Pelvis

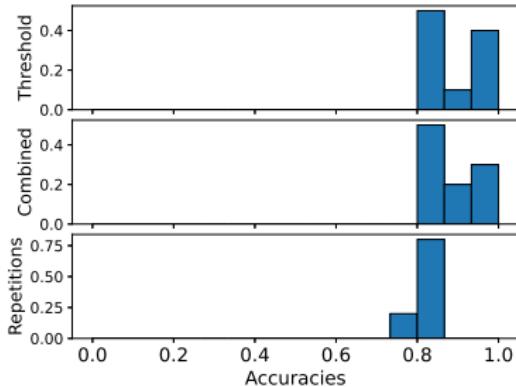


# Histograms over accuracies and F1 scores - Femoral Valgus

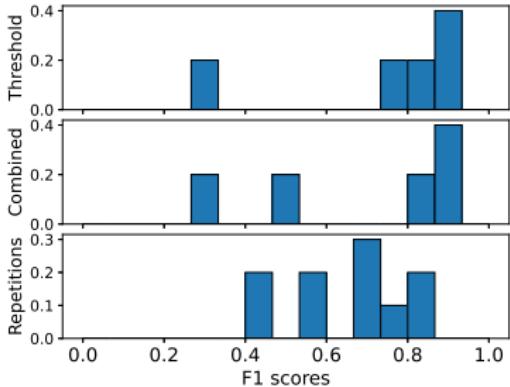


# Histograms over accuracies and F1 scores - KMFP

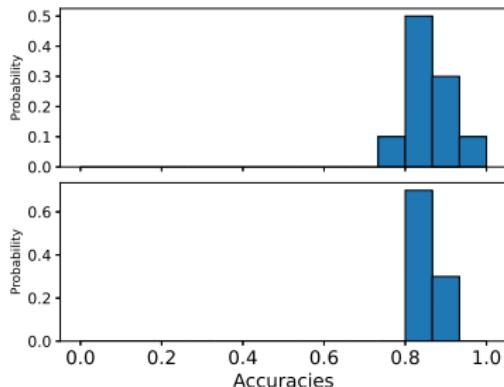
Accuracies



F1 scores



Accuracies for individual models



F1 scores for individual models

