Beta-project - Using AI to classify climbing problems

Climbing is a sportive discipline where participants must... climb, either indoor or outdoor. Here, we tackle indoor climbing: a wall contains holds, and the climber must only use some of them. A difficulty ("grade") is attributed following the pattern: (number in range 5-9)(letter in range a-c)(nothing or a + symbol) (for example: 5c+ or 8b).

The goal is to predict the grade of the route only using its physical properties, and not the feeling of the climber. We use Deep Learning algorithms inside a global Data science method to solve this problem.

This project uses data from Moonboard, a climbing board with customizable routes: holds that the climber can use are shown with LEDs. Thus, there is a great amount of possible routes, that can be graded by everyone using the Moonboard app. We'll thus consider that grades contained in this database are relevant, and we'll train and test our models against this data.

TODO:

- use k-fold (https://scikit-learn.org/stable/modules/generated/sklearn.model_selection.RepeatedKFold.htm ?)
- make merged graphics
- re-test every model and significant variations in order to show the effect of different techniques and their combination
- Do a better under-sampling (just removing some samples from majority class, and test training with max 1000 images per class) (add some data augmentation?)

General data consideration

We start our project by importing relevant Python libraries, for data science, visualization and machine learning. We'll tackle explainability later.

In [40]:

```
import json
import os
import datetime

import numpy as np
import pandas as pd
```

```python
import matplotlib.pyplot as plt
import seaborn as sns

import tensorflow as tf
import tensorflow.keras as keras

from IPython.display import Image
```

Download and import data

We use an extracted database found on GitHub.

We first download everything and import raw data, except the "problems.json" that mostly contains duplicates of the Masters 2019 dataset.

We include the Mini MoonBoard dataset, as it contains many routes that are still relevant to our problem. The model we'll use will not take into account the size of the route but rather local patterns.

We only include columns that will be relevant for our classification problem, i.e. data that influence a route's grade.

In [ ]:
```
!wget https://github.com/spookykat/MoonBoard/files/13193317/problems_2023_01
!unzip problems_2023_01_30 -d problems_2023_01_30
```

In [2]:
```python
columns = {
  "apiId": int,
  "name": str,
  "grade": 'category',
  "userGrade": 'category',
  "method": 'category',
  "holdsetup": 'category',
  "holdsets": 'object',
  "moves": 'object',
  "angle": int
}
column_names = list(columns.keys())

df = pd.DataFrame(columns=column_names)

for filename in os.listdir('problems_2023_01_30'):
  if filename == 'problems.json':
    continue

  with open(os.path.join('problems_2023_01_30', filename), 'r') as f:
    data = json.load(f)
    local_df = pd.DataFrame(data["data"])
    angle = int(filename.rstrip('.json').split()[-1])
    local_df['angle'] = angle if angle < 90 else 40
    df = pd.concat([df, local_df[column_names]])
```

```
df.drop_duplicates(keep='first', subset='apiId', inplace=True)
df.set_index('apiId', inplace=True)
```

Parse fields

Fields with foreign relations

In [3]:
```
df["holdsetup"] = df["holdsetup"].map(lambda x: x['apiId'])
df["holdsets"] = df["holdsets"].map(lambda sets: [el['apiId'] for el in sets
```

Moves: all holds of the route

There are three types of holds:

- Starter hold: where to put hands at the beginning
- Middle hold
- End hold: where to put both hands for at least 3 seconds at the end of the route

In [4]:
```
WIDTH = 11
HEIGHT = 18
NUM_HOLD_TYPES = 3

MOVES_SHAPE=(WIDTH, HEIGHT, NUM_HOLD_TYPES)

def parse_holds(moves):
  holds = np.zeros(MOVES_SHAPE, dtype=np.uint8)
  for hold in moves:
    description = hold['description']
    column = ord(description[0].upper()) - ord('A')
    row = int(description[1:]) - 1
    channel = 0
    if hold['isStart']:
      channel = 1
    if hold['isEnd']:
      channel = 2
    holds[column, row, channel] = 1
  return holds


df["moves"] = df["moves"].map(parse_holds)
```

Merging "grade" and "userGrade"

When a userGrade is present, it means that enough users rated this route so we assume this is a more objective metric than opener's grade attribution.

In [5]:
```
df["grade"] = df["userGrade"].combine_first(df["grade"]).astype('category')
df.drop("userGrade", axis=1, inplace=True)
```

Putting the right dtypes

In [6]:
```
for column in df.columns:
  df[column] = df[column].astype(columns[column])
```

Empty data

In [7]:
```
df.isna().sum()
```

Out[7]:
```
name         0
grade        0
method       0
holdsetup    0
holdsets     0
moves        0
angle        0
dtype: int64
```

There is no empty data, but one can uncomment the code below if any shows up.

In [8]:
```
# df.select_dtypes(include=[int, float]).fillna(df.mean(), inplace=True)
# categories = df.select_dtypes(include=['category', 'object'])
# categories.fillna(categories.mode().iloc[0])
```

Data Visualization and analysis

Overall information

In [9]:
```
df.describe()
```

Out[9]:

	angle
count	143100.000000
mean	38.548952
std	4.433996
min	25.000000
25%	40.000000
50%	40.000000
75%	40.000000
max	40.000000

In [10]:
```
df['holdsets'].value_counts()
```

Out[10]:
```
holdsets
[3, 4, 5]          32702
[4, 5]             24720
[4, 5, 8]          12873
[3, 4, 5, 8]        8615
[3, 4, 5, 8, 9]     4963
                   ...
[5, 9, 11]            53
[10]                  50
[5, 11]               47
[5, 9, 10]            43
[5, 10]               31
Name: count, Length: 78, dtype: int64
```

In [11]:
```
df['holdsetup'].value_counts()
```

Out[11]:
```
holdsetup
1     59506
15    55122
17    24802
19     3670
Name: count, dtype: int64
```

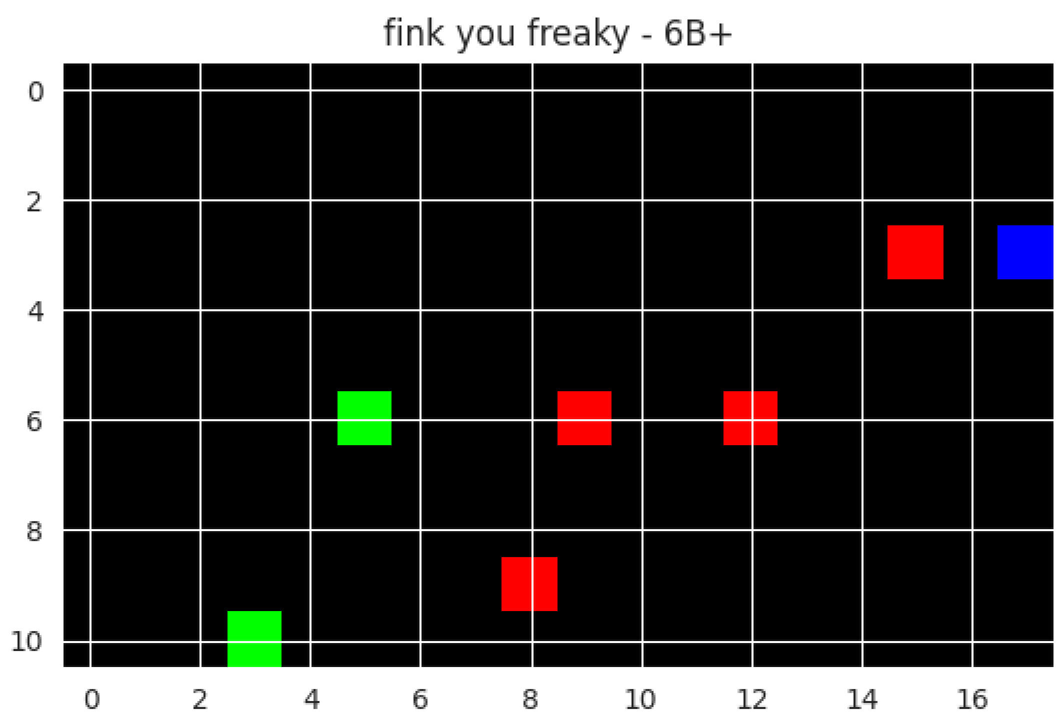
In [12]:
```
all_grades = list(df['grade'].cat.categories)
all_grades
```

Out[12]:
```
['5+',
 '6A',
 '6A+',
 '6B',
 '6B+',
 '6C',
 '6C+',
 '7A',
 '7A+',
 '7B',
 '7B+',
 '7C',
 '7C+',
 '8A',
 '8A+',
 '8B',
 '8B+']
```

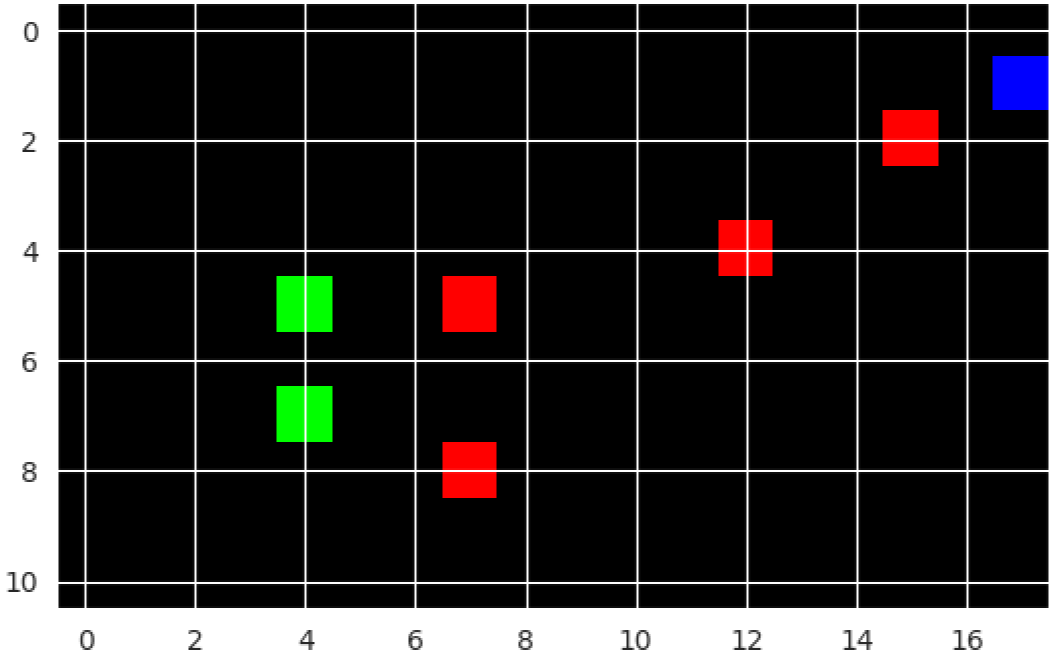
Visualize routes

We plot some of the routes to better visualize their structure. The plot will not be in the same orientation, due to the array structure: the left side is the bottom of the route.

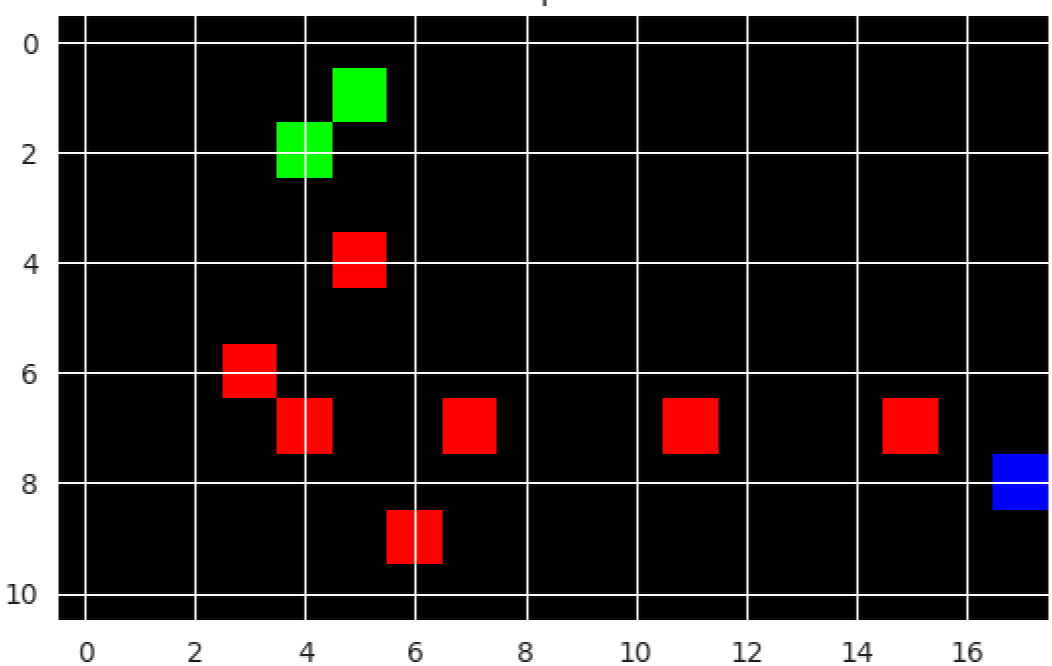
In [13]:
```
for _, route in df.sample(n=6).iterrows():
  plt.imshow(route['moves'] * 255)
  plt.title(f"{route['name']} - {route['grade']}")
  plt.show()
```



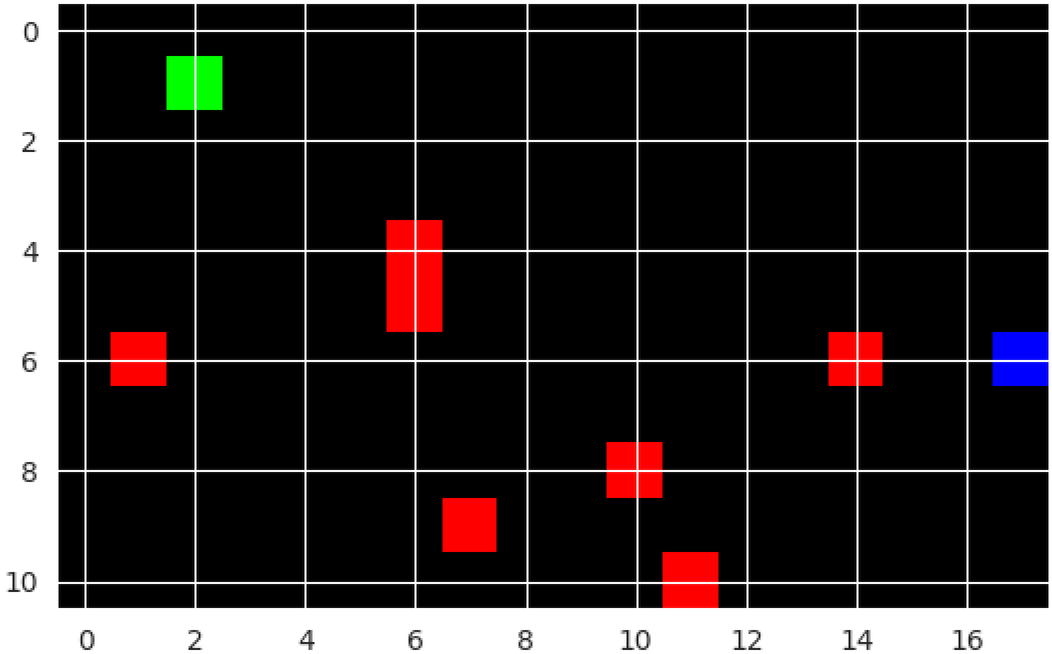
The G warmup - 6A+



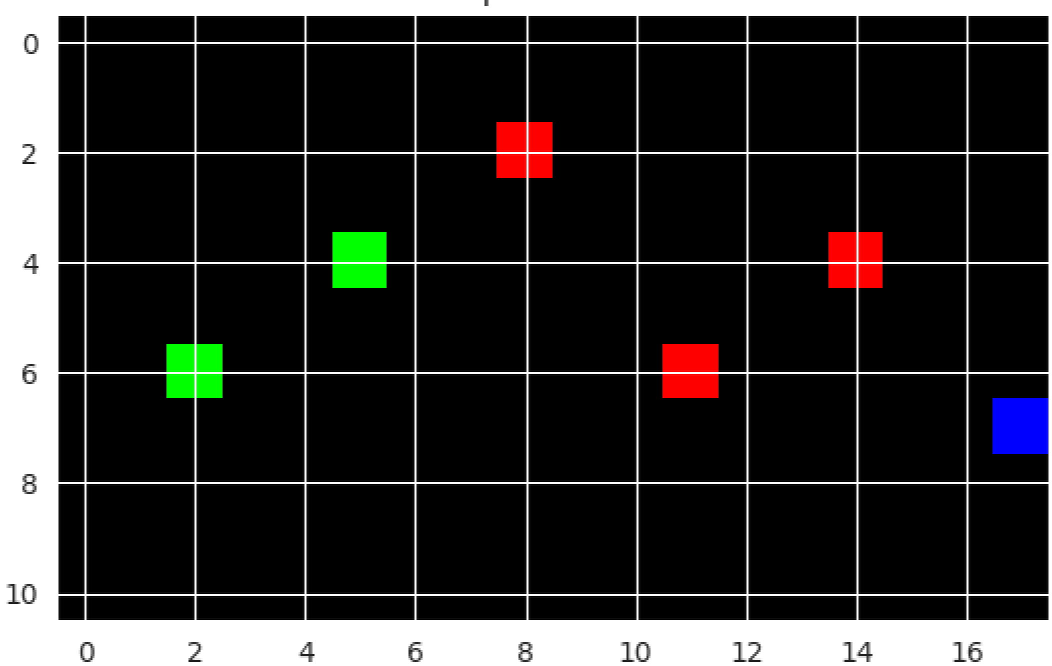
Traveque - 6C

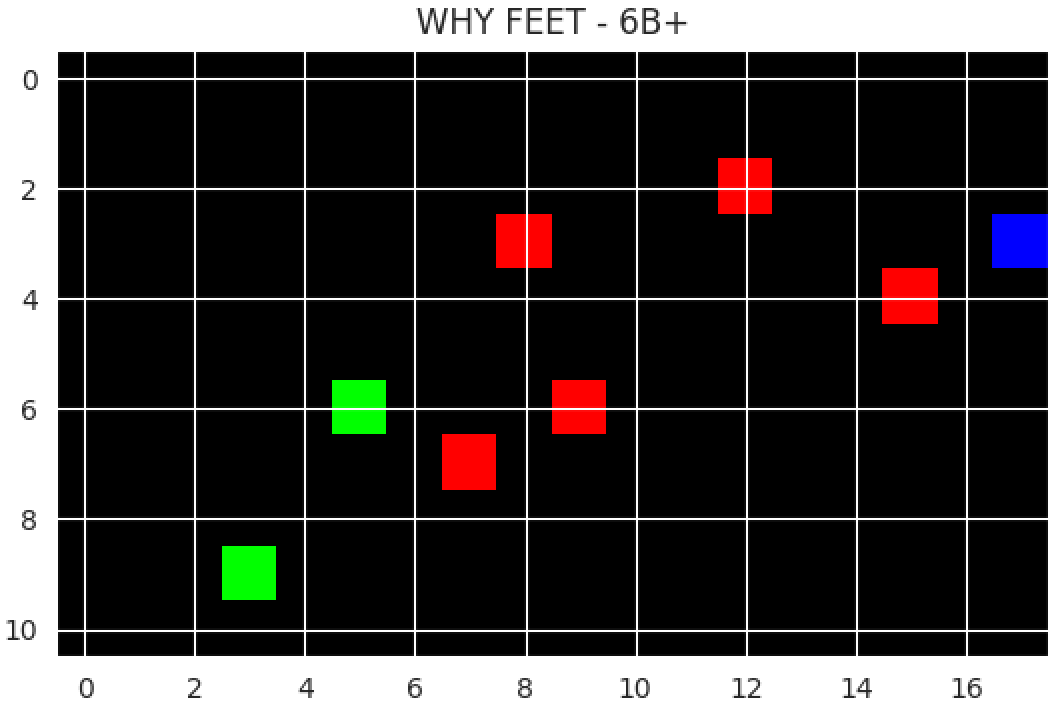


Clyde the glide - 7A+



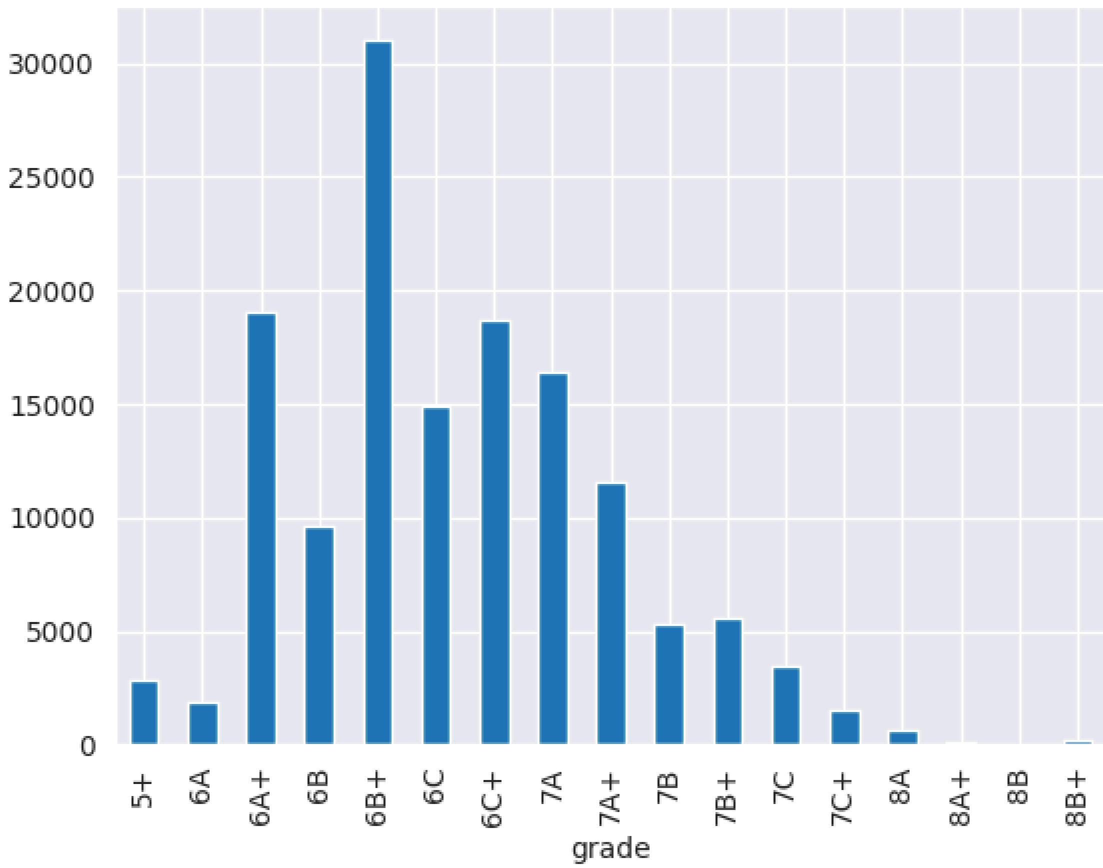
nap time - 7A





Plot the distribution of classes

In [14]:
```
def plot_category_hist(dataframe, cat):
  dataframe[cat].value_counts().sort_index().plot(kind='bar')

plot_category_hist(df, "grade")
```



Middle-grade routes are over-represented, with 6B+ routes being clearly omnipresent.

Check the influence of the resolution method

Let's see another field: "method", describing how the climber should physically solve the problem. This can significantly influence the difficulty and feasibility of a route.

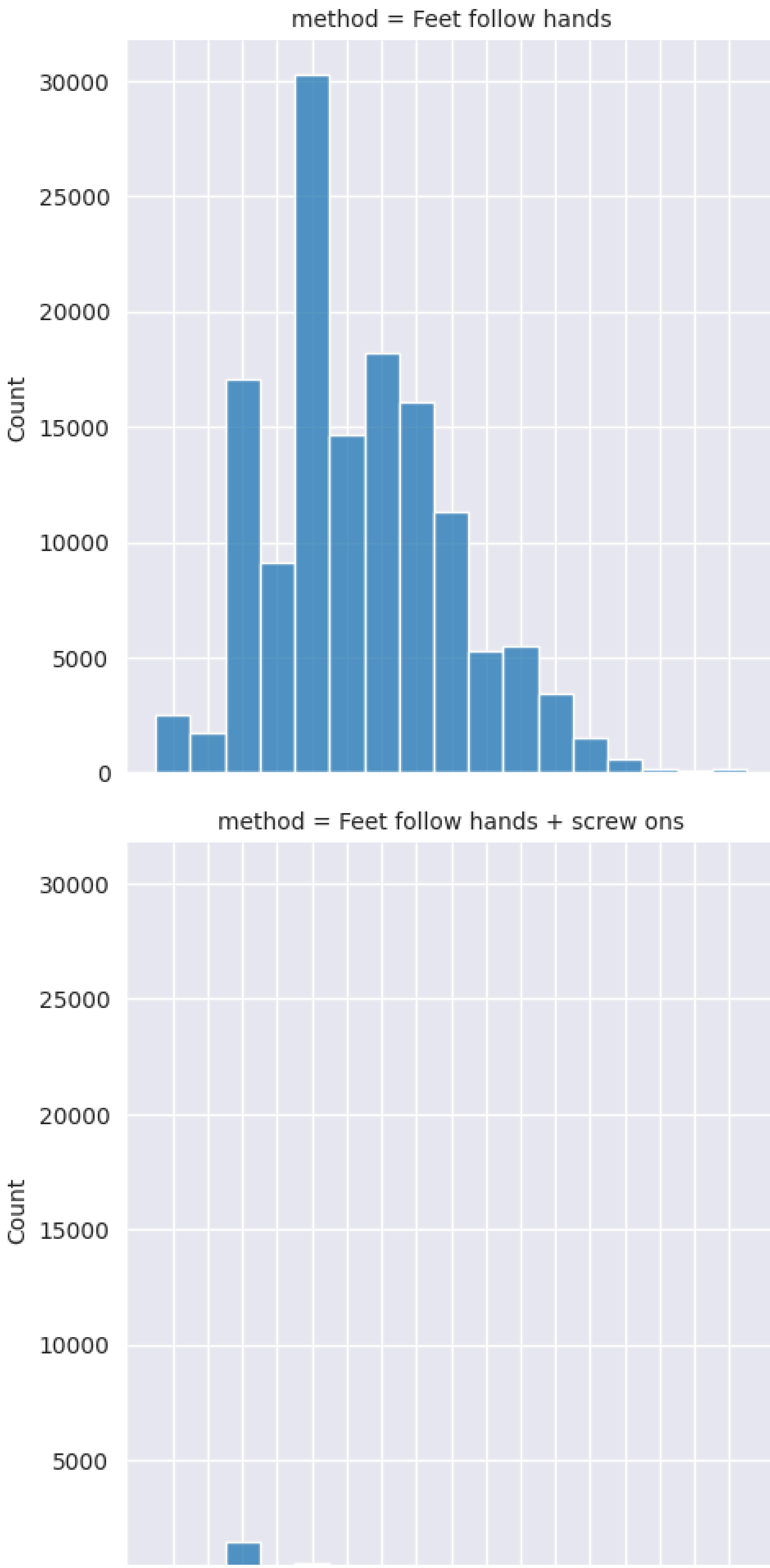
In [15]:
```
df.groupby('method').size() / len(df)
```

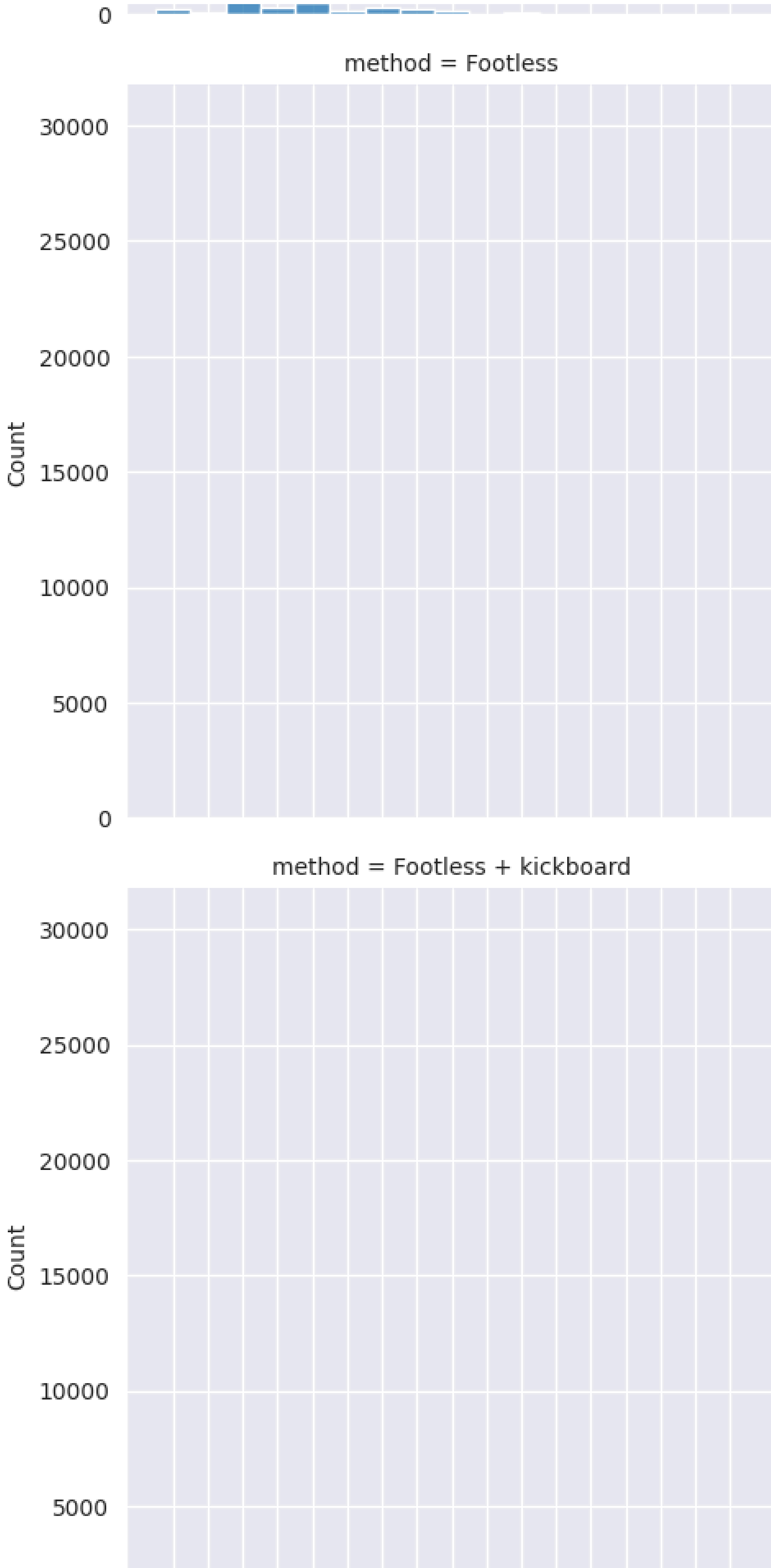
```
/tmp/ipykernel_38365/647761904.py:1: FutureWarning: The default of observed=False is deprecated and will be changed to True in a future version of pandas. Pass observed=False to retain current behavior or observed=True to adopt the future default and silence this warning.
  df.groupby('method').size() / len(df)
```

Out[15]:
```
method
Feet follow hands                  0.961579
Feet follow hands + screw ons      0.025618
Footless                           0.000021
Footless + kickboard               0.009553
Screw ons only                     0.003229
dtype: float64
```

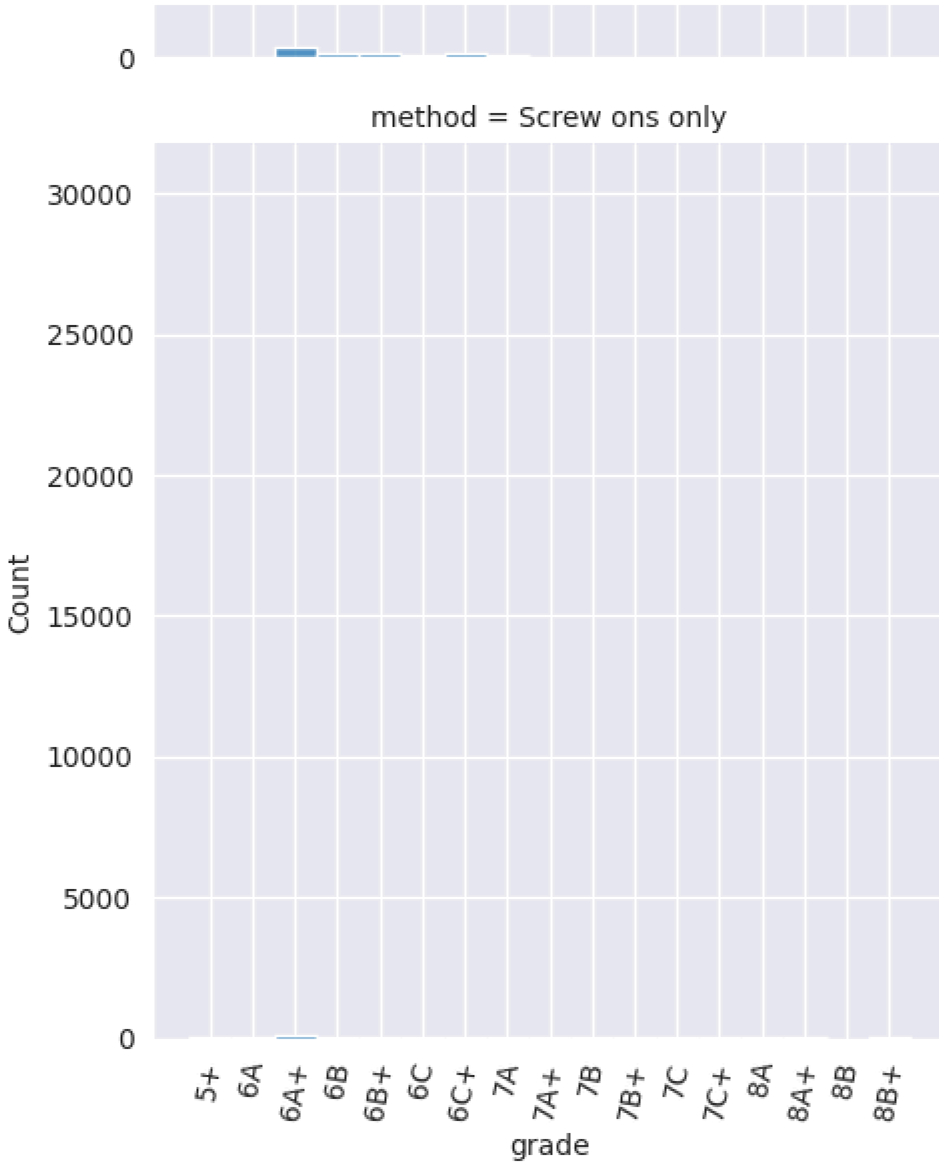
In [16]:
```python
nb_methods = len(df['method'].dtype.categories)

sns.displot(data=df, x='grade', row='method')
plt.xticks(rotation=80)
```

Out[16]:
```
([0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16],
 [Text(0, 0, '5+'),
  Text(1, 0, '6A'),
  Text(2, 0, '6A+'),
  Text(3, 0, '6B'),
  Text(4, 0, '6B+'),
  Text(5, 0, '6C'),
  Text(6, 0, '6C+'),
  Text(7, 0, '7A'),
  Text(8, 0, '7A+'),
  Text(9, 0, '7B'),
  Text(10, 0, '7B+'),
  Text(11, 0, '7C'),
  Text(12, 0, '7C+'),
  Text(13, 0, '8A'),
  Text(14, 0, '8A+'),
  Text(15, 0, '8B'),
  Text(16, 0, '8B+')])
```


method = Feet follow hands
Count
30000
25000
20000
15000
10000
5000
0
method = Feet follow hands + screw ons
Count
30000
25000
20000
15000
10000
5000



0
method = Footless
30000
25000
20000
15000
10000
5000
0
Count
method = Footless + kickboard
30000
25000
20000
15000
10000
5000
Count



Data Preparation

We now want to prepare our data specifically for Machine Learning. We'll apply several well-known techniques, such as encoding (one-hot, rare...) and normalization, in order for our models to learn as much relevant data as possible to generalize well. We'll finish by splitting the data into training and testing sets - the validation set is created directly when training a new model.

Separate features and labels

We keep `moves` separate, as it's a special data type that we can tackle in many different ways. We'll see later two views: as a simple sequence, or as images.

In [17]:
```
features = df.drop(columns=['moves', 'grade', 'name'])
moves = df['moves']
labels = df['grade']
```

Rare encoding

For each categorical feature, we group together categories that appear less than 1% of the time.

For instance, the `method` feature has a clear imbalance: thus values `footless`, `footless + kickboard` and `screw ons only` must be gathered together. We can see this group as "difficult", as the climber is not allowed to use their feet for these routes.

In [18]:
```
rare_threshold = 0.1

for col in features.select_dtypes(include=['category']):
  value_counts = features[col].value_counts()
  rare_values = list(value_counts[value_counts / len(features) < rare_thresh
  if len(rare_values) > 1:
    features[col] = features[col].cat.add_categories(['Rare'])
    features.loc[features[col].isin(rare_values), col] = 'Rare'
    features[col] = features[col].cat.remove_unused_categories()
```

One-hot encoding

Before going further, we need to convert all features except 'moves' to numerical ones.

Dealing with the `holdsets` feature

This field contain arrays of holdsets, so we'll use a one-hot encoding to indicate for each holdset if a route contains it.

In [19]:
```
# TODO: use https://scikit-learn.org/stable/modules/preprocessing_targets.ht

def flatten_array(arr):
  result = []
  for el in arr:
    result.extend(el)
  return result

all_sets = list(features['holdsets'].value_counts().index)
all_sets = flatten_array(all_sets)
all_sets = list(set(all_sets))
```

```
for i in all_sets:
  features[f'holdset_{i}'] = False
```

In [20]:
```
def encode_sets(x):
  for i in x['holdsets']:
    x[f'holdset_{i}'] = True
  return x

features = features.apply(encode_sets, axis=1)
features.drop(columns=['holdsets'], inplace=True)
```

Dealing with other features

We use a basic one-hot encoding for other features, which is done quickly using pandas.

In [21]:
```
features['holdsetup'] = features['holdsetup'].astype('category')
features = pd.get_dummies(features)

labels = pd.get_dummies(labels)
```

Now that we have all the columns, we can get the number of distinct features and labels:

In [22]:
```
nb_labels = len(labels.columns)
nb_features = len(features.columns)
```

Normalization

We use min-max normalization, as the distribution of numerical inputs (i.e. `angle`) is not normal.

In [23]:
```
for col in features.select_dtypes(include=[int, float]):
  features[col] = (features[col] - features[col].min()) / (features[col].max
```

Split into train and test datasets

As explained earlier, the validation dataset will be created directly when fitting the model.

In [24]:
```
from sklearn.model_selection import train_test_split

test_split = 0.2

train_features, test_features, train_moves, test_moves, train_labels, test_l
  features,
  moves,
  labels,
```

```
  test_size=test_split,
  stratify=labels,
)

train_moves = np.stack(train_moves.values)
test_moves = np.stack(test_moves.values)
```

Helpers to build, train and analyse models

In this part, we define some helpers functions that we are going to reuse for all models : from building a model to analysing results.

Skeleton: build and fit model

We first define a function to plot a model, which can be useful to verify the connections made, especially as our models will not be sequential.

In [25]:
```
def plot_model(model):
  keras.utils.plot_model(
    model,
    show_shapes=True,
    show_dtype=True,
    show_layer_names=True,
    show_layer_activations=True,
    expand_nested=True
  )
```

For all models, we use the Categorical Crossentropy by default, as we face a multi-label classification problem, but where each object only has a unique class.

We also use different accuracy metrics not to rely only on the basic accuracy. Indeed, in the reality of climbing, it is okay to be one grade off - in many cases, the climber won't really notice the difference.

In [26]:
```
def compile_model(
        model=None,
        build_function=None,
        learning_rate=1e-3,
        loss=keras.losses.CategoricalCrossentropy(),
        metrics=None):

    if model is None:
        model = build_function()

    if metrics is None:
        metrics=[]
```

```
    metrics.extend([
      keras.metrics.CategoricalAccuracy(name='accuracy'),
      keras.metrics.TopKCategoricalAccuracy(k=3, name='accuracy_at_three'),
      keras.metrics.TopKCategoricalAccuracy(k=5, name='accuracy_at_five')
    ])

    model.compile(
        optimizer=keras.optimizers.RMSprop(learning_rate=learning_rate),
        loss=loss,
        metrics=metrics
    )
    return model
```

Finally, we create the function to train models. We use several callbacks to save our models at intermediary and "best-accuracy" stages, as well as exporting data for TensorBoard. This will allow us to precisely analyse our results and plot relevant graphs.

In [27]:
```
def train_model(model,
                training_features,
                training_labels,
                epochs=100,
                callbacks=None,
                early_stopping=None,
                validation_split=0.2,
                batch_size=64,
                class_weight=None,
                name='model',
                log_dir='logs/fit'
                ):

    if callbacks is None:
        callbacks = []

    if early_stopping is not None:
        callbacks.append(keras.callbacks.EarlyStopping(monitor='loss', patie

    date = datetime.datetime.now().strftime("%Y%m%d-%H%M%S")
    callbacks.extend([
      keras.callbacks.ModelCheckpoint(f'models/{name}-{date}-{{epoch:02d}}-{
      keras.callbacks.ModelCheckpoint(f'models/{name}-{date}-best.keras', sa
      keras.callbacks.BackupAndRestore(backup_dir=f'/tmp/backup/{name}--{dat
      keras.callbacks.TensorBoard(log_dir=f'{log_dir}/{name}--{date}', histo
    ])

    model.fit(
      training_features,
      training_labels,
      epochs=epochs,
      callbacks=callbacks,
      validation_split=validation_split,
      batch_size=batch_size,
      class_weight=class_weight,
```

```
    )
    return model
```

Skeleton: overall accuracy

In [28]:
```
from sklearn.metrics import accuracy_score, balanced_accuracy_score
from sklearn.metrics import confusion_matrix
```

In [29]:
```
def parse_prediction(model, moves, features, labels):
  probabilities_labels = model.predict([moves, features], verbose=0)
  y_true = np.argmax(labels, axis=1)
  y_pred = np.argmax(probabilities_labels, axis=1)
  predicted = np.zeros_like(probabilities_labels).astype(bool)
  predicted[np.arange(probabilities_labels.shape[0]), y_pred] = True

  return predicted, y_true, y_pred


def load_best_model(
        name='model',
  ):
    best_model = keras.models.load_model(f'models/{name}-best.keras')
    train_predicted, train_y_true, train_y_pred = parse_prediction(best_mode
    test_predicted, test_y_true, test_y_pred = parse_prediction(best_model,

    return best_model, train_predicted, train_y_true, train_y_pred, test_pre
```

In [30]:
```
def print_accuracies(model, y_true, y_pred):
  metrics = model.evaluate([test_moves, test_features], test_labels, verbose
  print(f'Accuracy: {metrics[1] * 100:.2f}%')
  print(f'Balanced Accuracy: {balanced_accuracy_score(y_true, y_pred) * 100:
  print(f'Accuracy for Top3: {metrics[2] * 100:.2f}%')
  print(f'Accuracy for Top5: {metrics[3] * 100:.2f}%')
```

In [31]:
```
def confusion_matrix_analysis(y_true, y_pred):
  cm = confusion_matrix(y_true, y_pred)
  cm_normalized = cm.astype('float') / cm.sum(axis=1)[:, np.newaxis]

  per_class_accuracy = cm.diagonal() / cm.sum(axis=1)
  for i, acc in enumerate(per_class_accuracy):
    print(f"Accuracy for grade {all_grades[i]}: {acc * 100:.2f}%")

  plt.figure(figsize=(15, 10))
  sns.heatmap(cm_normalized,  annot=True, fmt='.2f', cmap='rocket')
  plt.xlabel("Predicted Labels")
  plt.ylabel("True Labels")
  plt.title("Normalized Confusion Matrix")
  plt.show()
```

Skeleton: one-vs-rest analysis

In [32]:
```
def create_one_vs_rest_plot(xlabel, ylabel):
  fig, axs = plt.subplots(nrows=nb_labels, ncols=1, sharex=True)
  fig.set_size_inches(6, 4 * nb_labels)
  fig.text(0.5, 0.0005, xlabel, ha='center')
  fig.text(0.04, 0.5, ylabel, va='center', rotation='vertical')
  return fig, axs
```

In [33]:
```
from sklearn.metrics import roc_curve

def one_vs_rest_roc_curve(train_predicted, test_predicted):
  fig, axs = create_one_vs_rest_plot('False Positive Rate', 'True Positive R

  for i in range(nb_labels):
    train_fpr, train_tpr, _ = roc_curve(train_labels.values[:, i], train_pre
    test_fpr, test_tpr, _ = roc_curve(test_labels.values[:, i], test_predict
    plt.sca(axs[i])
    sns.lineplot(x=train_fpr, y=train_tpr, label='Train', ax=axs[i])
    sns.lineplot(x=test_fpr, y=test_tpr, label='Test', ax=axs[i])
    plt.ylabel(all_grades[i])

  fig.tight_layout()
```

In [34]:
```
from sklearn.metrics import precision_recall_curve

def one_vs_rest_precision_recall_curve(train_predicted, test_predicted):
  fig, axs = create_one_vs_rest_plot('False Positive Rate', 'True Positive R

  for i in range(nb_labels):
    train_precision, train_recall, _ = precision_recall_curve(train_labels.v
    test_precision, test_recall, _ = precision_recall_curve(test_labels.valu
    plt.sca(axs[i])
    sns.lineplot(x=train_precision, y=train_recall, ax=axs[i])
    sns.lineplot(x=test_precision, y=test_recall, ax=axs[i])
    plt.ylabel(all_grades[i])

  fig.tight_layout()
```

Baseline

For the baseline, we'll use a simple neural network with only Dense layers. We could even go simpler, but our final goal here is to implement a Deep Learning technique, so we only compare these kinds of algorithms.

In [36]:
```
def create_baseline():
  moves_inputs = keras.Input(shape=MOVES_SHAPE, name="moves")
  features_inputs = keras.Input(shape=(nb_features,), name="features")

  x = keras.layers.Flatten()(moves_inputs)

  x = keras.layers.concatenate([x, features_inputs])
```

```python
    x = keras.layers.Dense(256, activation='relu')(x)
    x = keras.layers.Dense(64, activation='relu')(x)
    x = keras.layers.Dropout(0.5)(x)
    outputs = keras.layers.Dense(nb_labels, activation='softmax')(x)

    return keras.Model(inputs=[moves_inputs, features_inputs], outputs=outputs
```

In [37]:

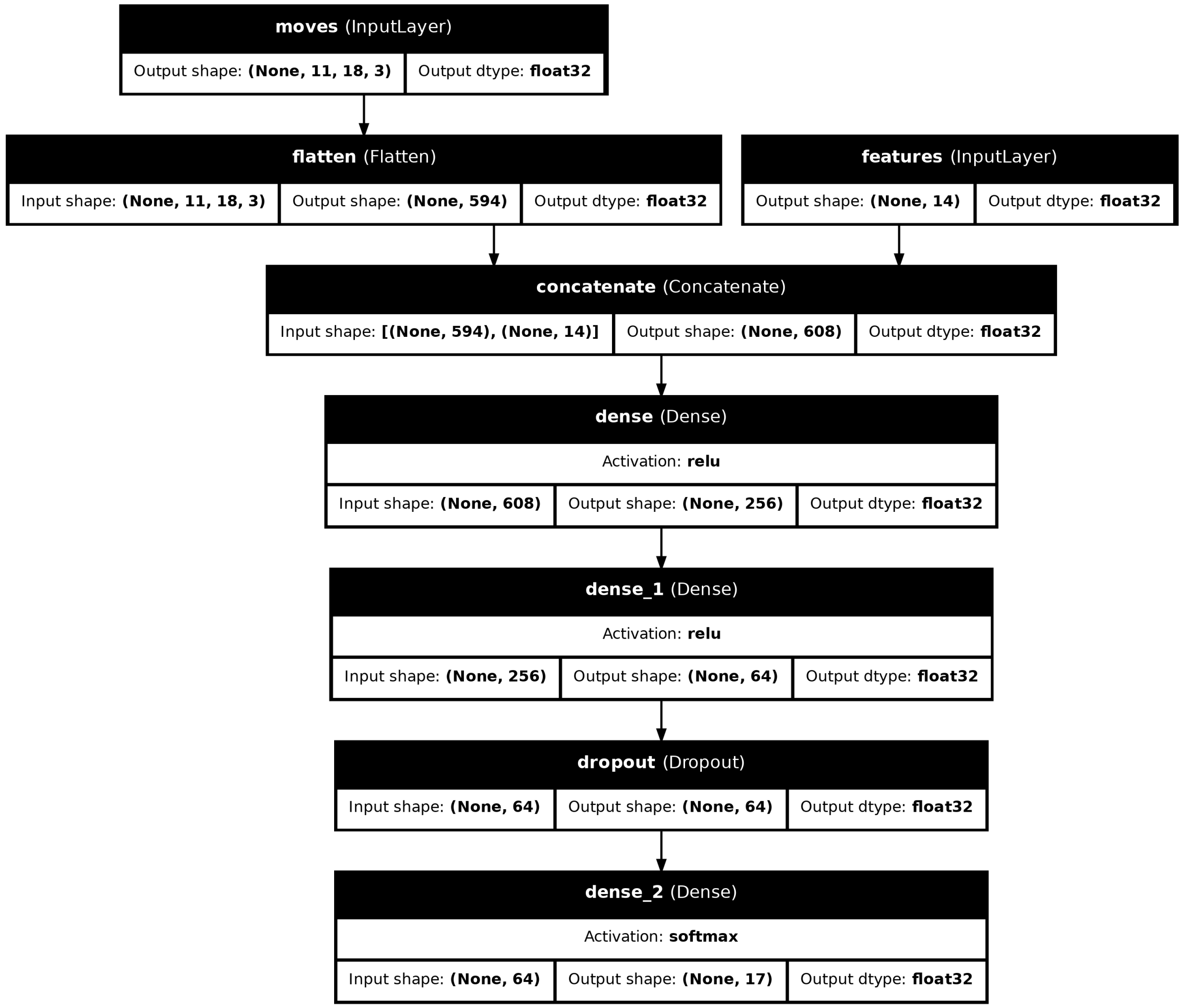
```python
baseline_model = compile_model(build_function=create_baseline)
```

```
WARNING: All log messages before absl::InitializeLog() is called are written
to STDERR
I0000 00:00:1728922446.239452   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.039767   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.040699   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.067376   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.067845   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.068172   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.371114   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.372271   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
I0000 00:00:1728922448.372929   38365 cuda_executor.cc:1015] successful NUMA
node read from SysFS had negative value (-1), but there must be at least one
NUMA node, so returning NUMA node zero. See more at https://github.com/torva
lds/linux/blob/v6.0/Documentation/ABI/testing/sysfs-bus-pci#L344-L355
2024-10-14 18:14:08.378750: I tensorflow/core/common_runtime/gpu/gpu_device.
cc:2021] Created device /job:localhost/replica:0/task:0/device:GPU:0 with 90
9 MB memory:  -> device: 0, name: NVIDIA GeForce GTX 1050, pci bus id: 0000:
01:00.0, compute capability: 6.1
```

In [41]:

```python
plot_model(baseline_model)
Image('model.png')
```

Out[41]:



Model training

In [ ]:

```
train_model(
  model=baseline_model,
  name='baseline',
  training_features=[train_moves, train_features],
  training_labels=train_labels,
  epochs=50,
  early_stopping=3
)
```

In [42]:

```
baseline_model, train_predicted, train_y_true, train_y_pred, test_predicted,
```

```
2024-10-14 18:15:52.685508: W external/local_tsl/tsl/framework/cpu_allocator
_impl.cc:83] Allocation of 68001120 exceeds 10% of free system memory.
2024-10-14 18:15:52.791539: W external/local_tsl/tsl/framework/cpu_allocator
_impl.cc:83] Allocation of 68001120 exceeds 10% of free system memory.
WARNING: All log messages before absl::InitializeLog() is called are written
to STDERR
I0000 00:00:1728922553.074954   38571 service.cc:146] XLA service 0x7fce6000
52a0 initialized for platform CUDA (this does not guarantee that XLA will be
used). Devices:
I0000 00:00:1728922553.075341   38571 service.cc:154]   StreamExecutor devic
e (0): NVIDIA GeForce GTX 1050, Compute Capability 6.1
2024-10-14 18:15:53.196211: I tensorflow/compiler/mlir/tensorflow/utils/dump
_mlir_util.cc:268] disabling MLIR crash reproducer, set env var `MLIR_CRASH_
REPRODUCER_DIRECTORY` to enable.
2024-10-14 18:15:53.417612: I external/local_xla/xla/stream_executor/cuda/cu
da_dnn.cc:531] Loaded cuDNN version 8907
I0000 00:00:1728922554.102502   38571 device_compiler.h:188] Compiled cluste
r using XLA!  This line is logged at most once for the lifetime of the proce
ss.
```

Accuracy

In [43]:
```
print_accuracies(baseline_model, test_y_true, test_y_pred)
```

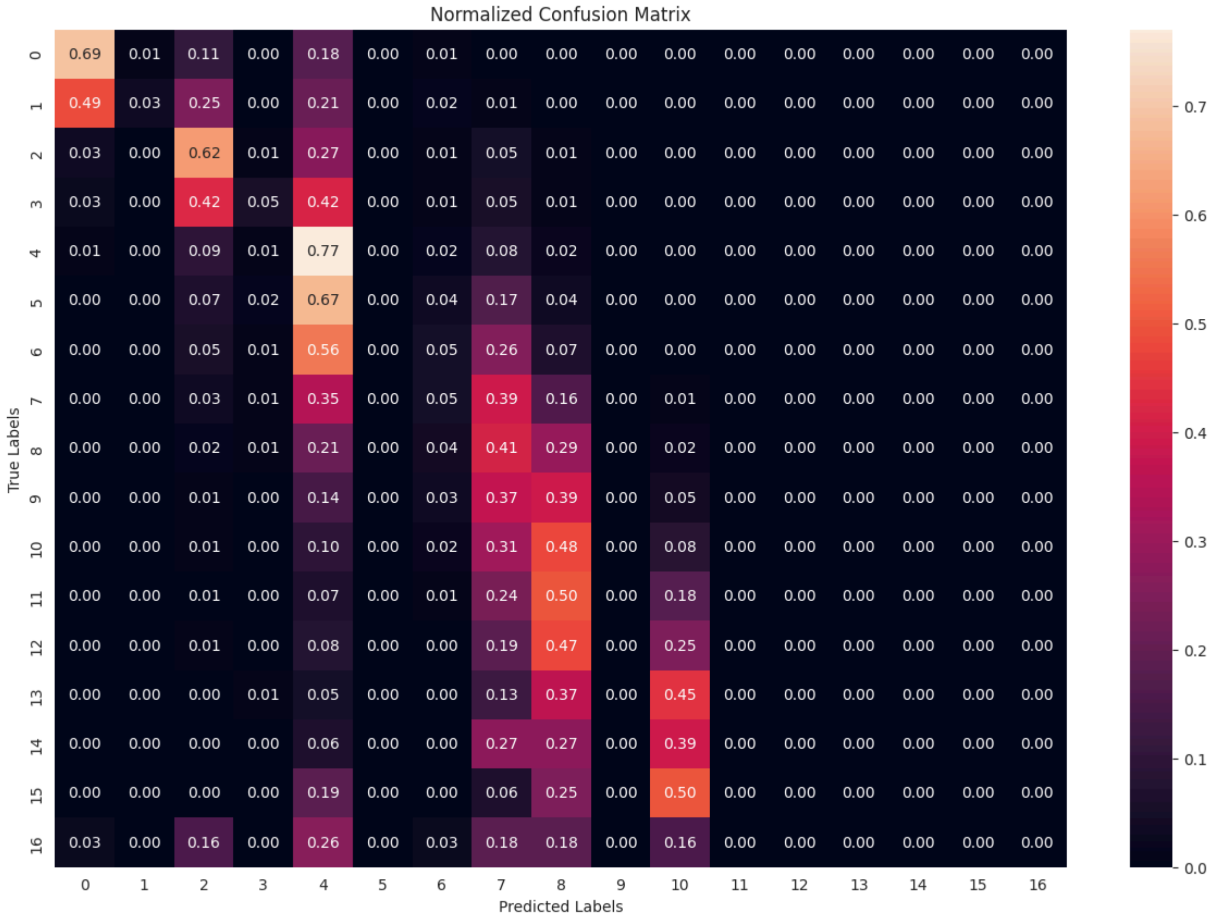
```
Accuracy: 34.48%
Balanced Accuracy: 17.54%
Accuracy for Top3: 68.28%
Accuracy for Top5: 86.37%
```

Our model is overfitting straight away: it's not able to detect any patterns, so it learns the training dataset by heart.

Confusion matrix

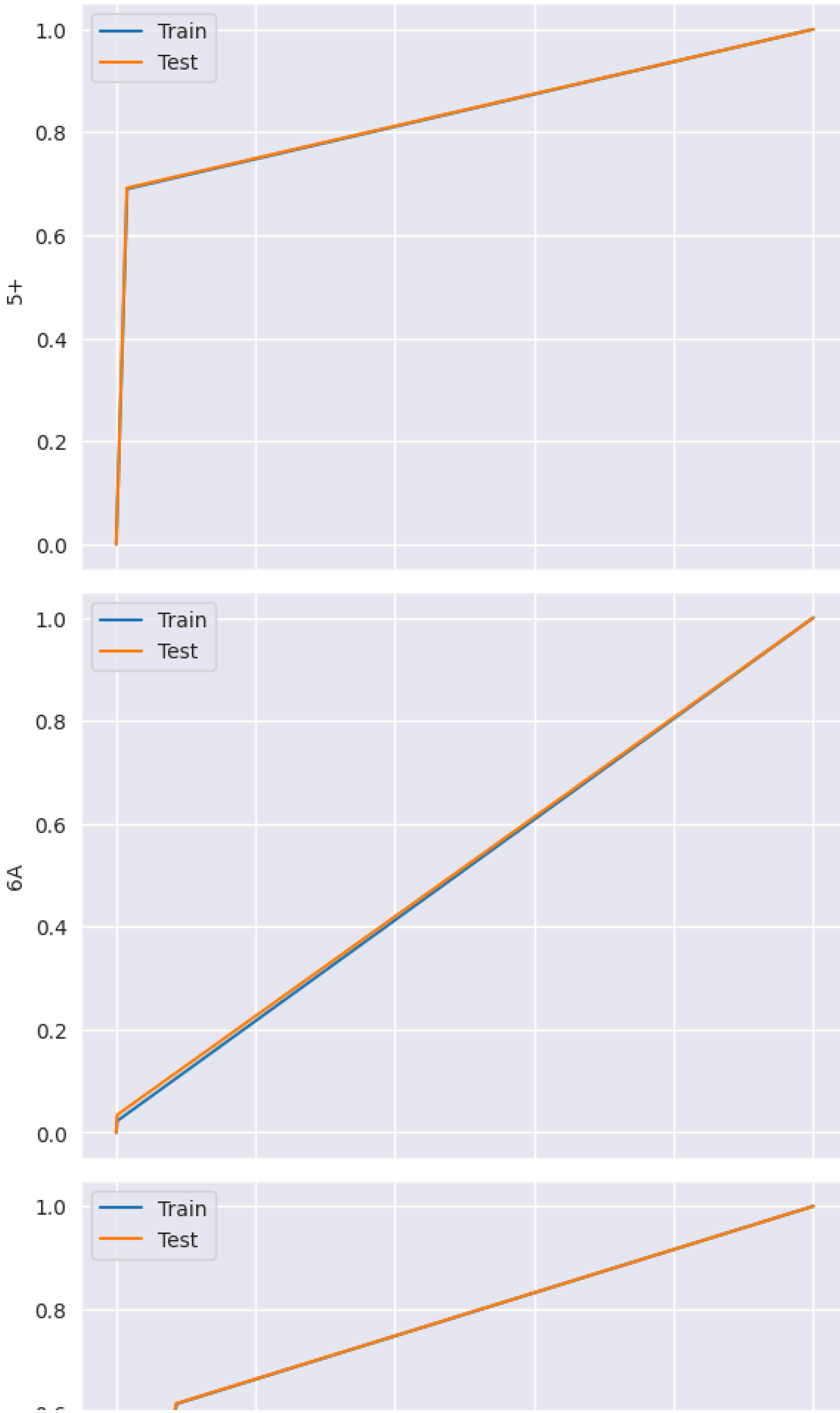
In [44]:
```
confusion_matrix_analysis(test_y_true, test_y_pred)
```

```
Accuracy for grade 5+: 69.18%
Accuracy for grade 6A: 3.43%
Accuracy for grade 6A+: 61.66%
Accuracy for grade 6B: 5.48%
Accuracy for grade 6B+: 77.02%
Accuracy for grade 6C: 0.13%
Accuracy for grade 6C+: 4.73%
Accuracy for grade 7A: 39.32%
Accuracy for grade 7A+: 29.07%
Accuracy for grade 7B: 0.00%
Accuracy for grade 7B+: 8.24%
Accuracy for grade 7C: 0.00%
Accuracy for grade 7C+: 0.00%
Accuracy for grade 8A: 0.00%
Accuracy for grade 8A+: 0.00%
Accuracy for grade 8B: 0.00%
Accuracy for grade 8B+: 0.00%
```

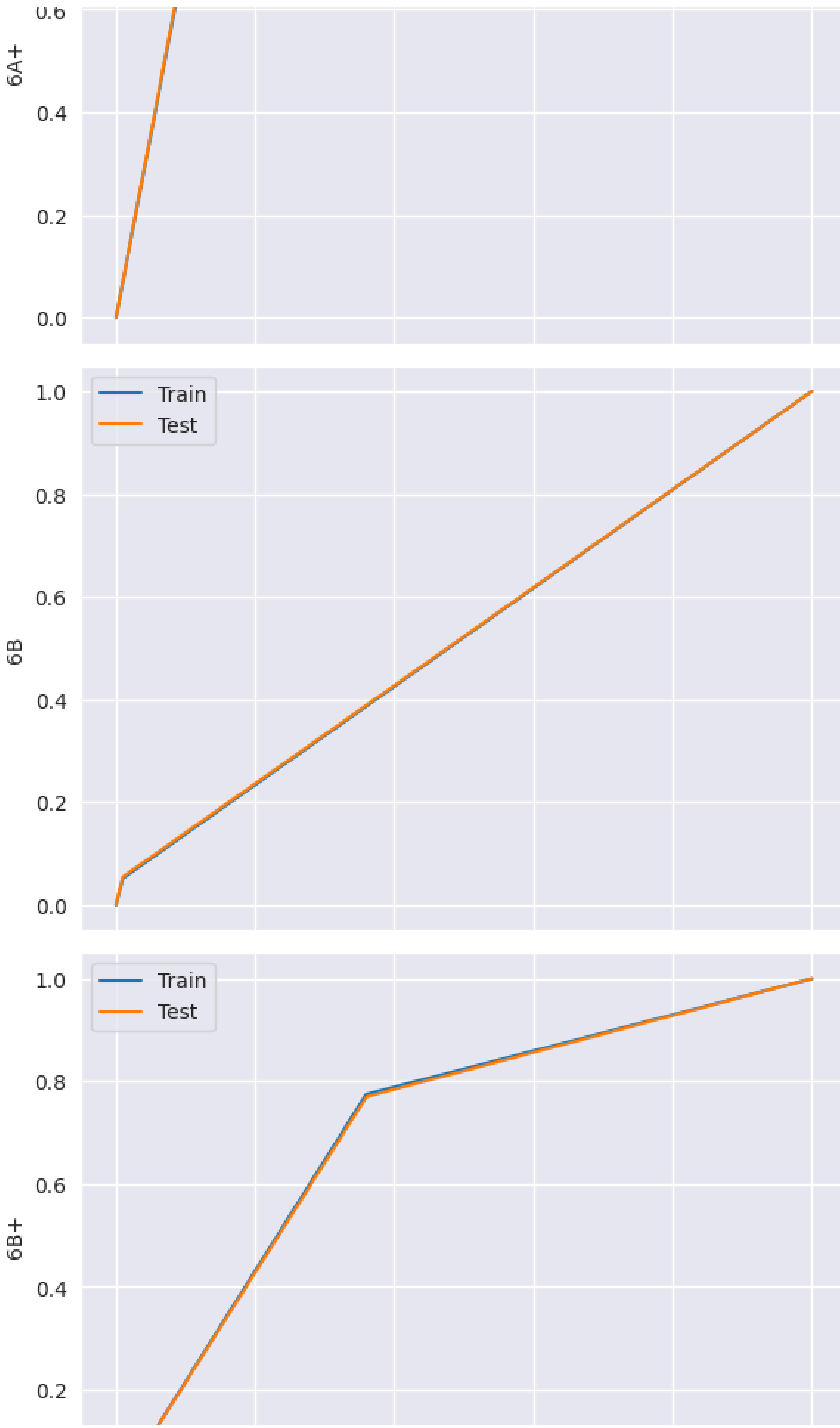


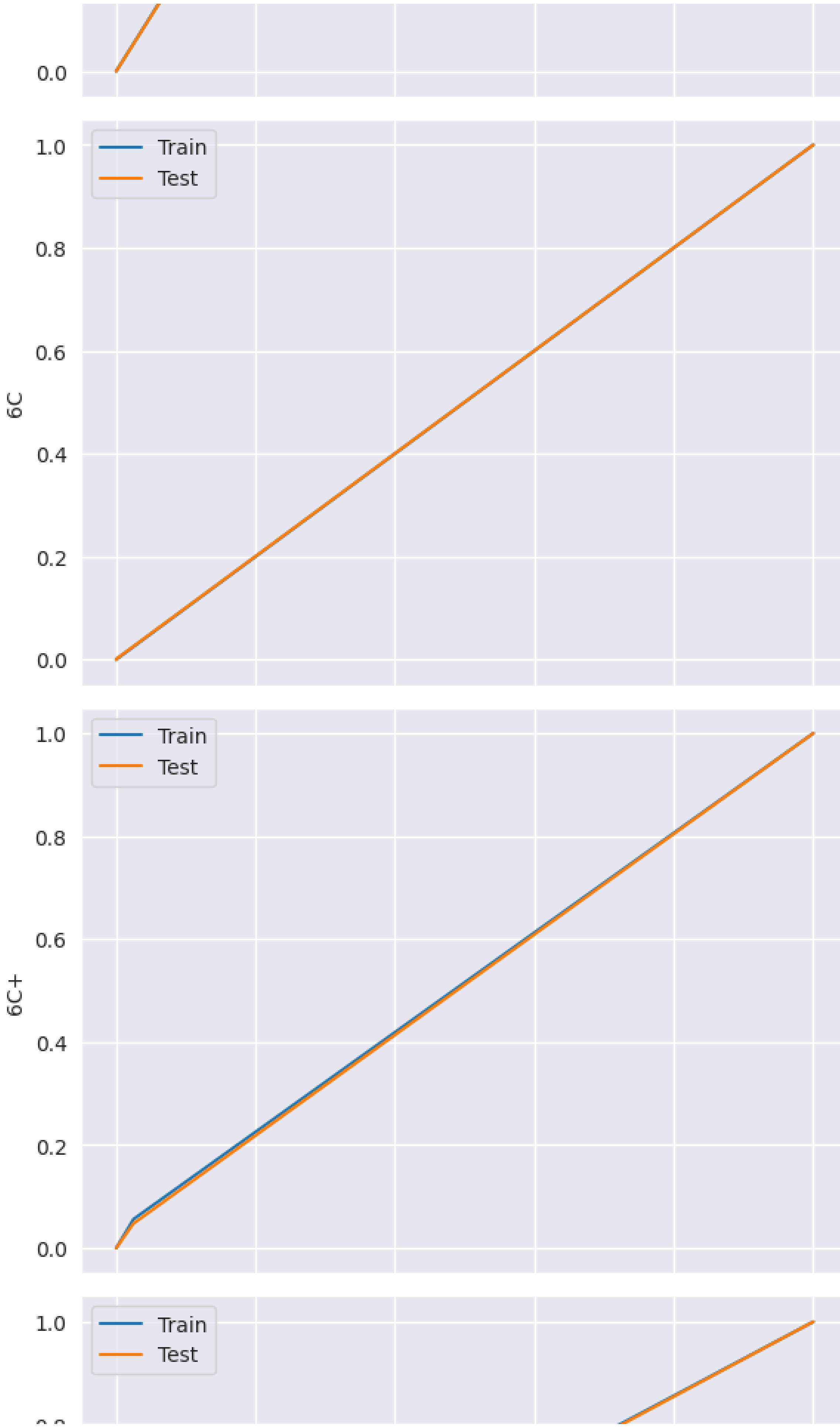
One-vs-rest analysis

In [45]:
```
one_vs_rest_roc_curve(train_predicted, test_predicted)
```

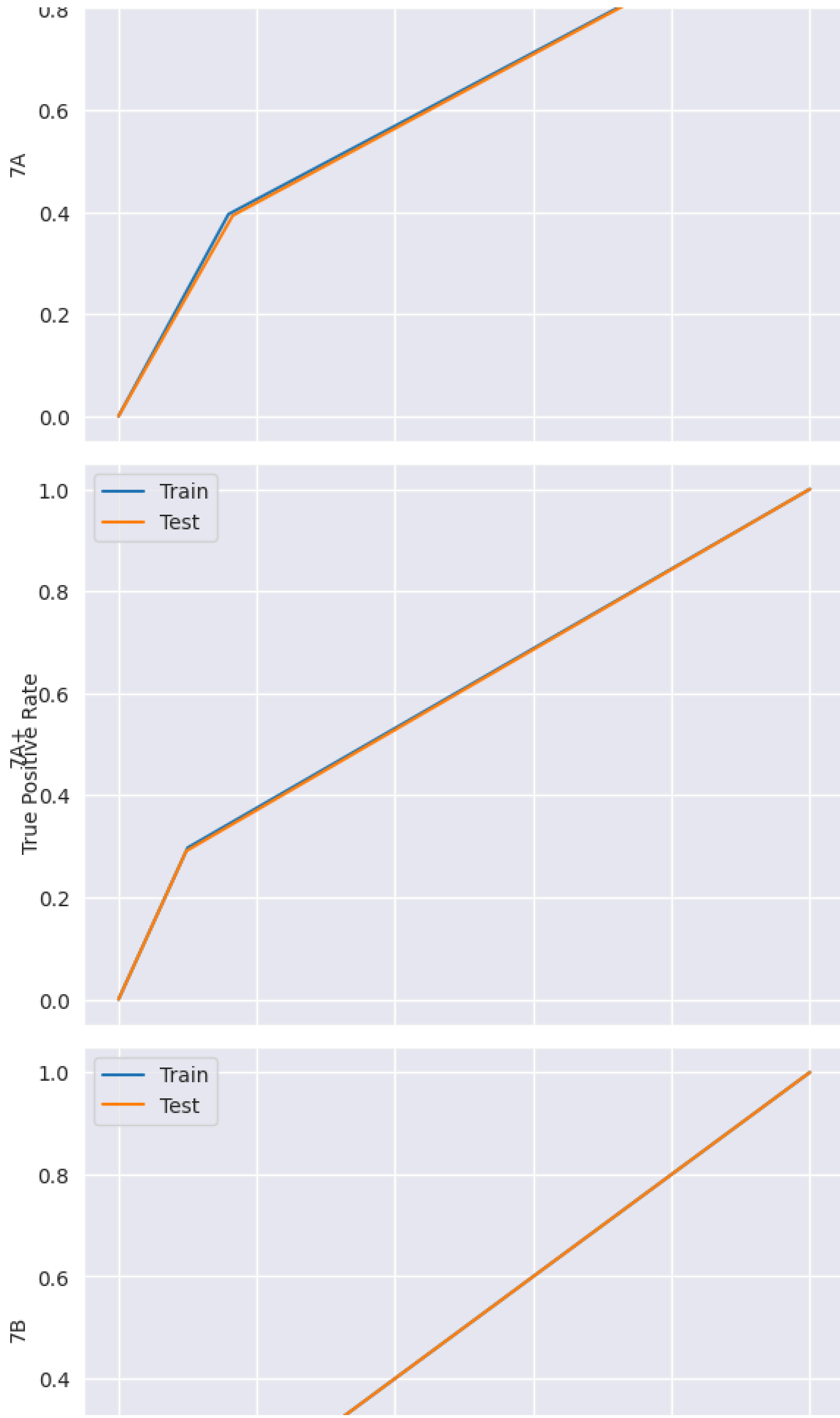


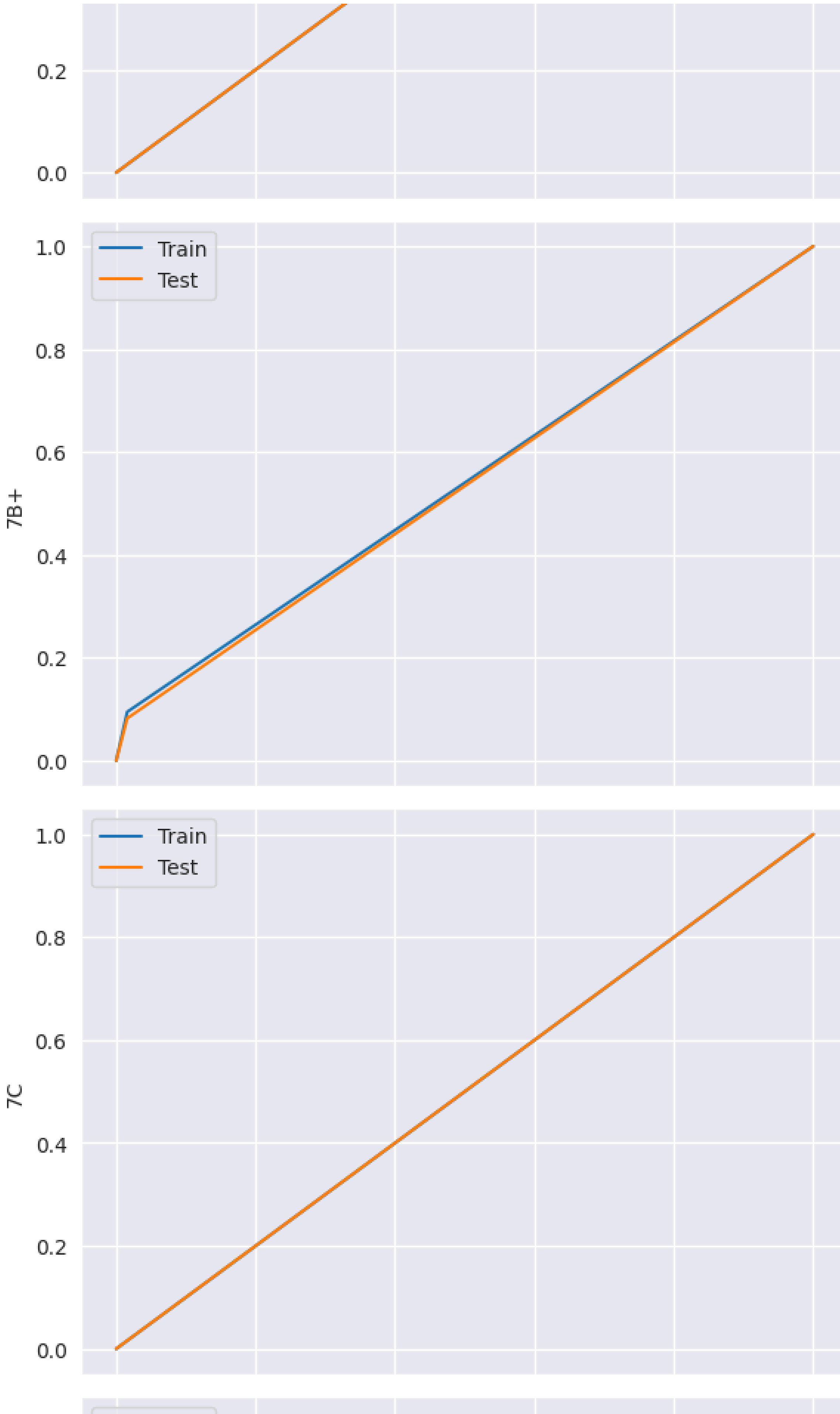
Train
Test
1.0
0.8
0.6
0.4
0.2
0.0
5+
Train
Test
1.0
0.8
0.6
0.4
0.2
0.0
6A
Train
Test
1.0
0.8


6A+
0.6
0.4
0.2
0.0
6B
1.0
0.8
0.6
0.4
0.2
0.0
Train
Test
6B+
1.0
0.8
0.6
0.4
0.2
Train
Test

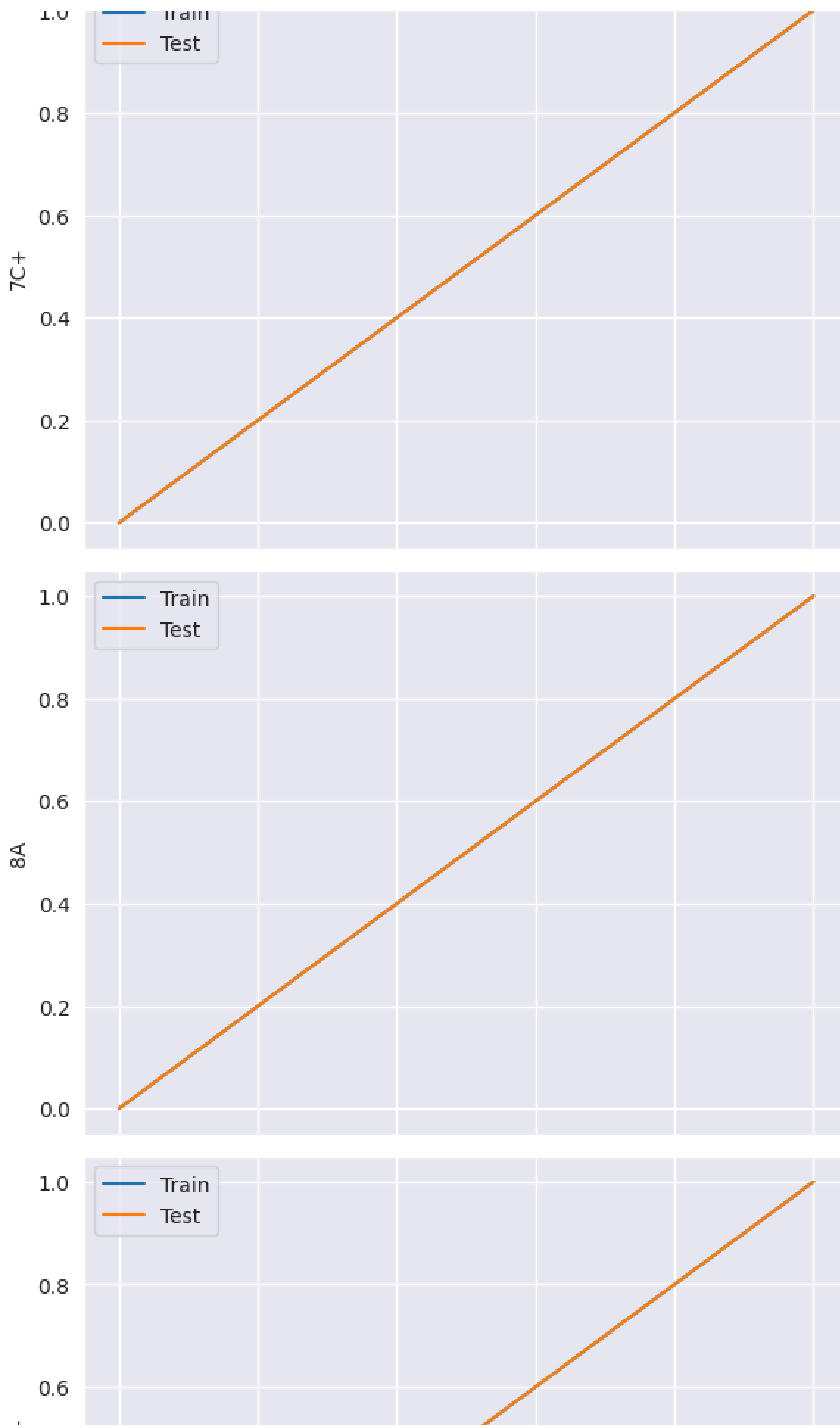


0.0
Train
Test
1.0
0.8
0.6
6C
0.4
0.2
0.0
Train
Test
1.0
0.8
0.6
6C+
0.4
0.2
0.0
Train
Test
1.0


0.8
0.6
0.4
0.2
0.0
7A
Train
Test
1.0
0.8
0.6
0.4
0.2
0.0
7A+
True Positive Rate
Train
Test
1.0
0.8
0.6
0.4
7B

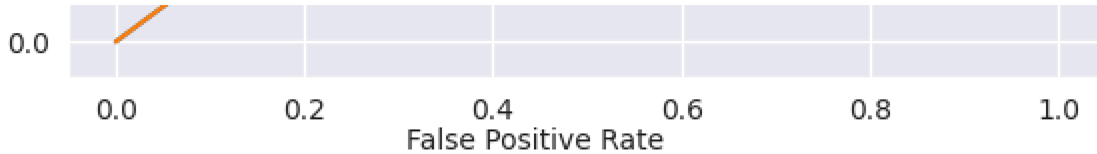


0.2
0.0
Train
Test
1.0
0.8
0.6
7B+
0.4
0.2
0.0
Train
Test
1.0
0.8
0.6
7C
0.4
0.2
0.0



Train
Test
7C+
0.0
0.2
0.4
0.6
0.8
1.0
8A

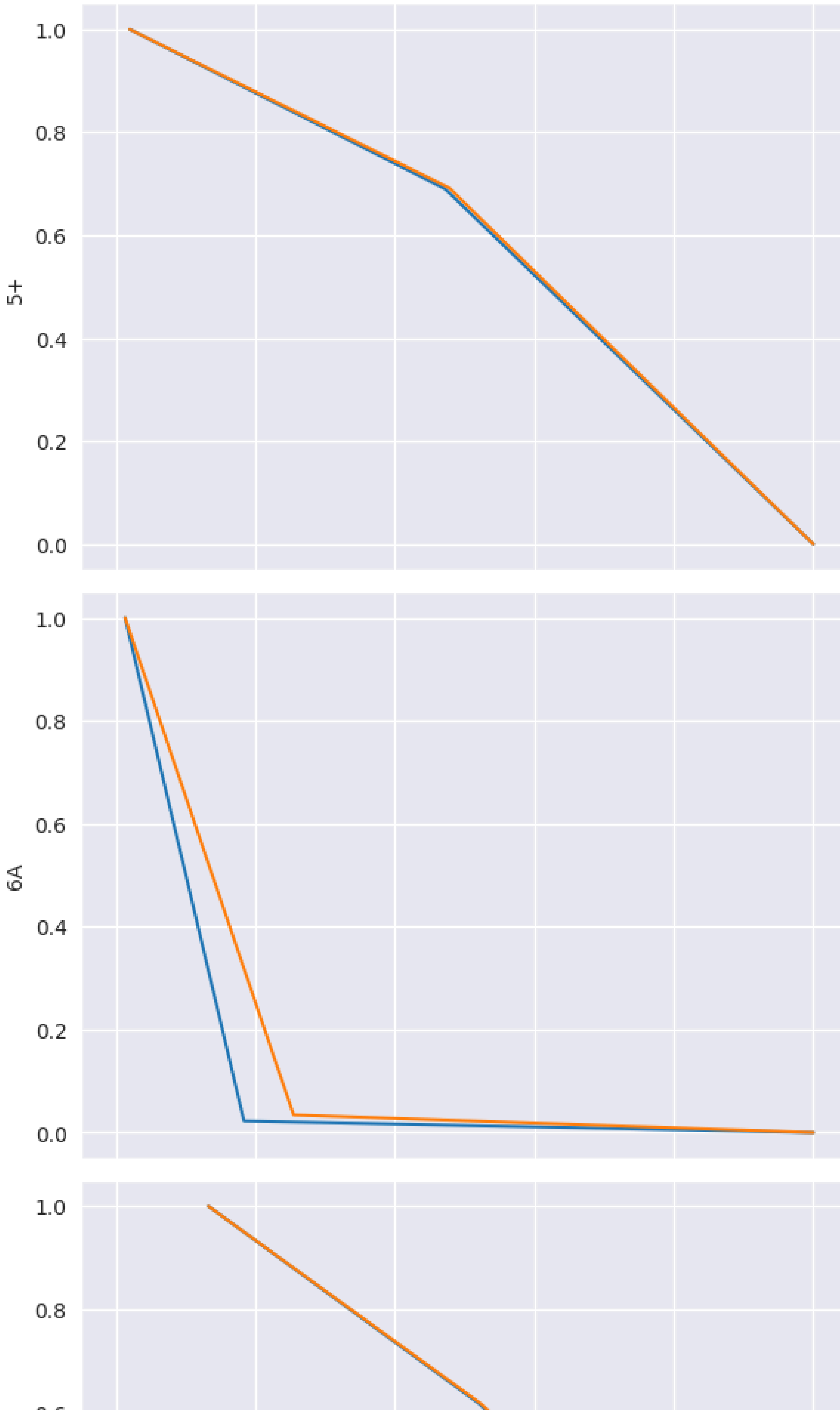

8A+
0.4
0.2
0.0
1.0
0.8
0.6
8B
0.4
0.2
0.0
Train
Test
1.0
0.8
0.6
8B+
0.4
0.2
Train
Test



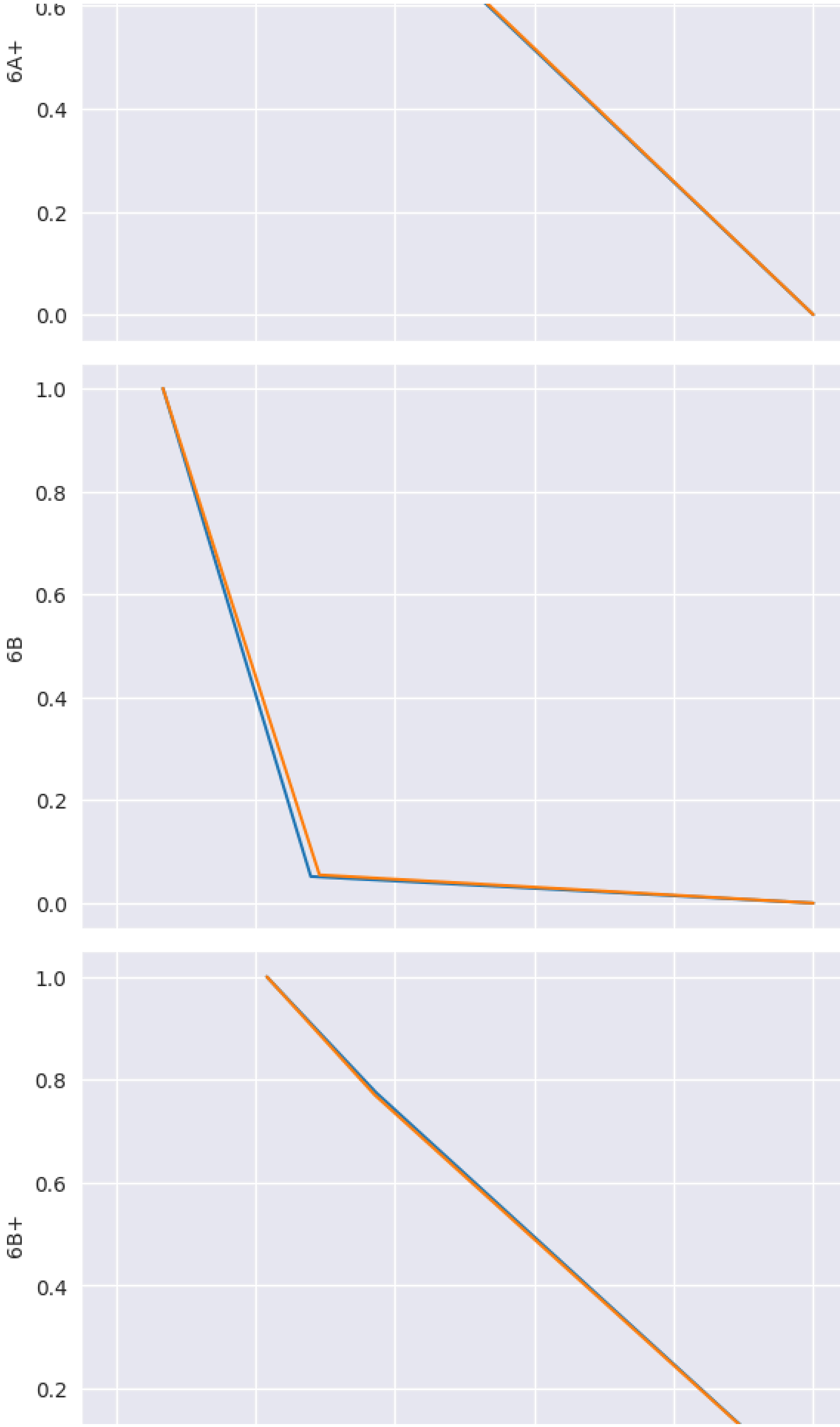
For almost every grade, this baseline model doesn't achieve better performance than a random guess. At least, it's not worse.

For middle grades (around 6), we get the same insight as with the confusion matrix: the model achieves better performance. Thus the class imbalance has a clear impact and we must apply corrections before going further.

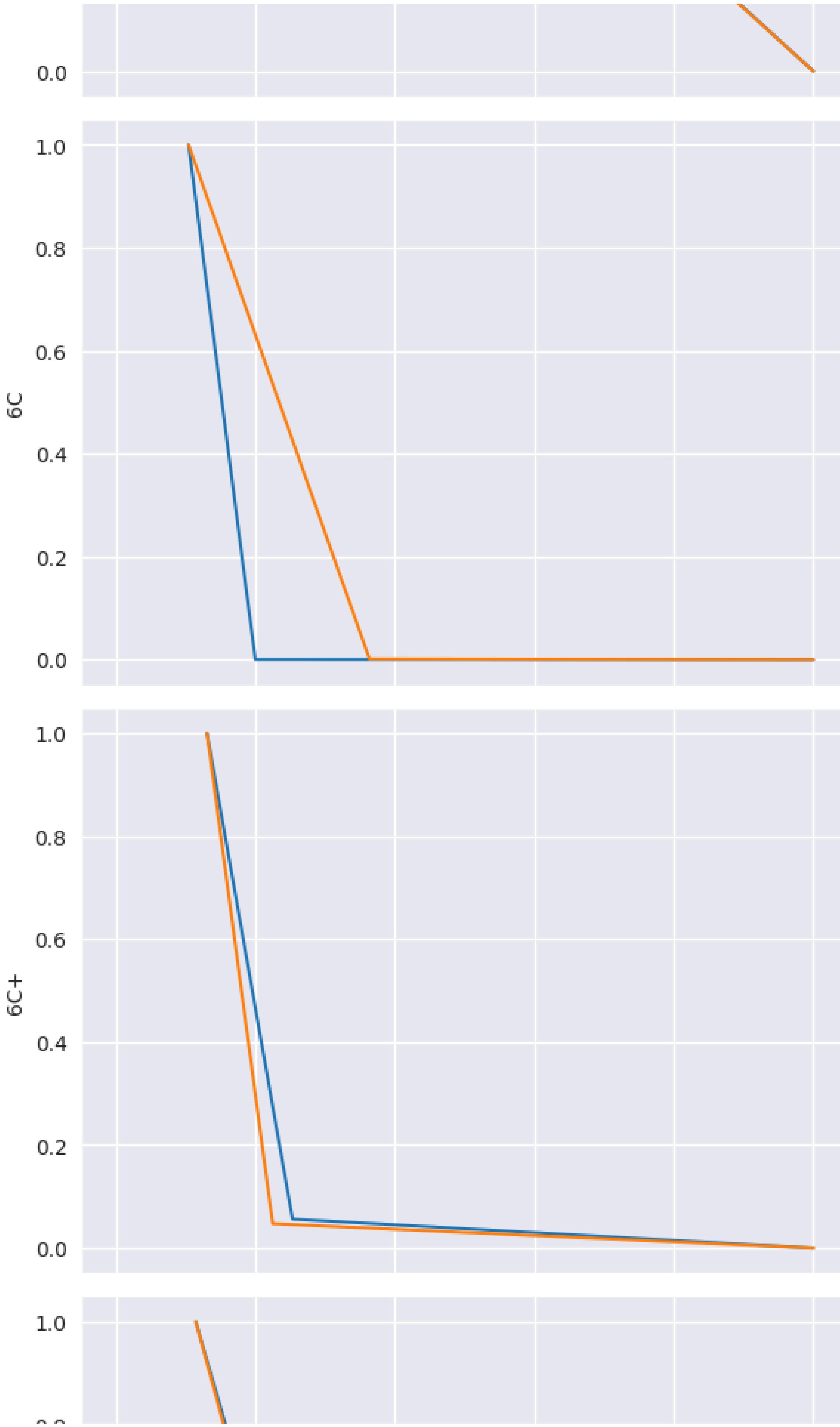
In [46]:
```
one_vs_rest_precision_recall_curve(train_predicted, test_predicted)
```

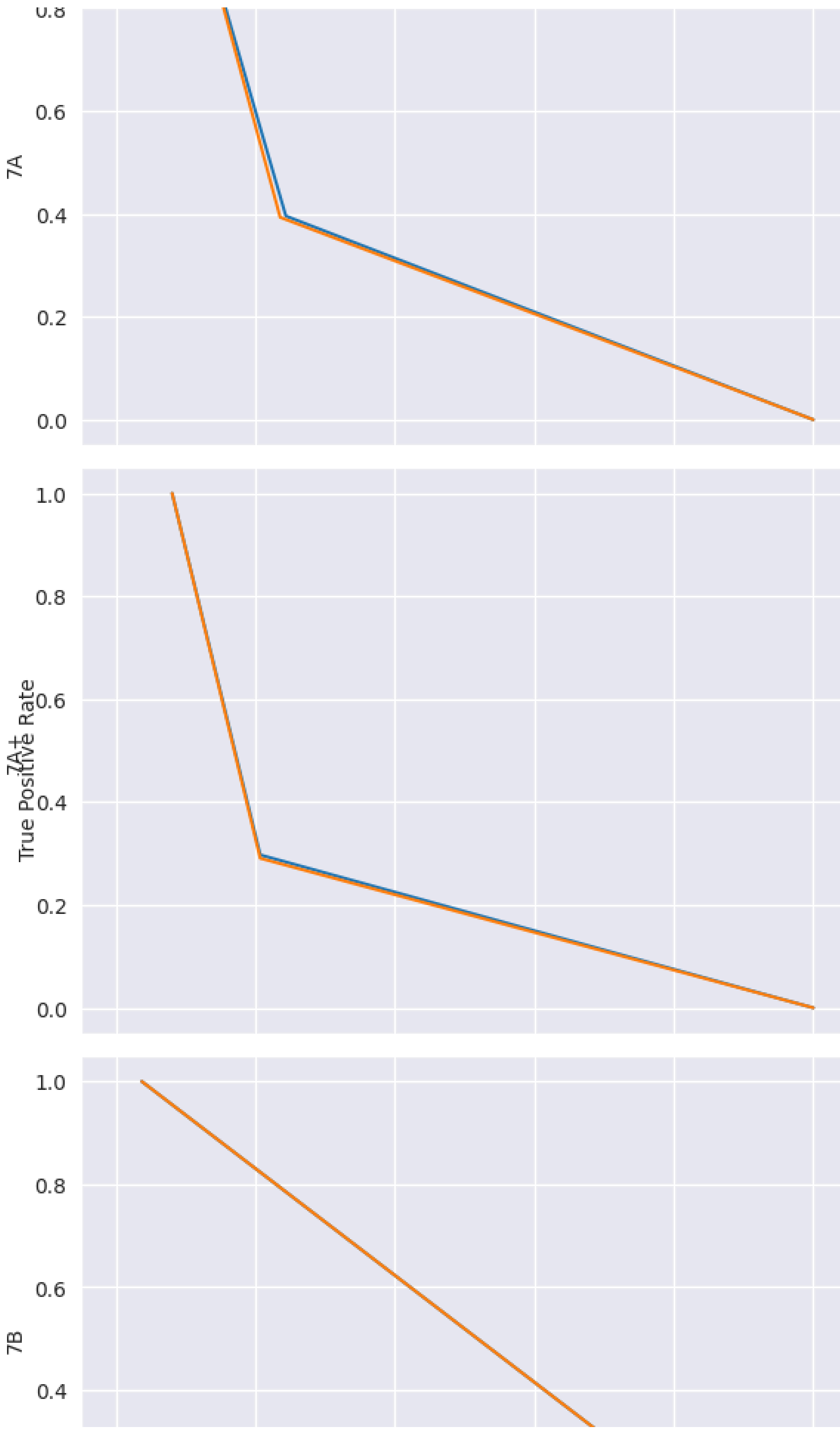


1.0
0.8
0.6
5+
0.4
0.2
0.0
1.0
0.8
0.6
6A
0.4
0.2
0.0
1.0
0.8

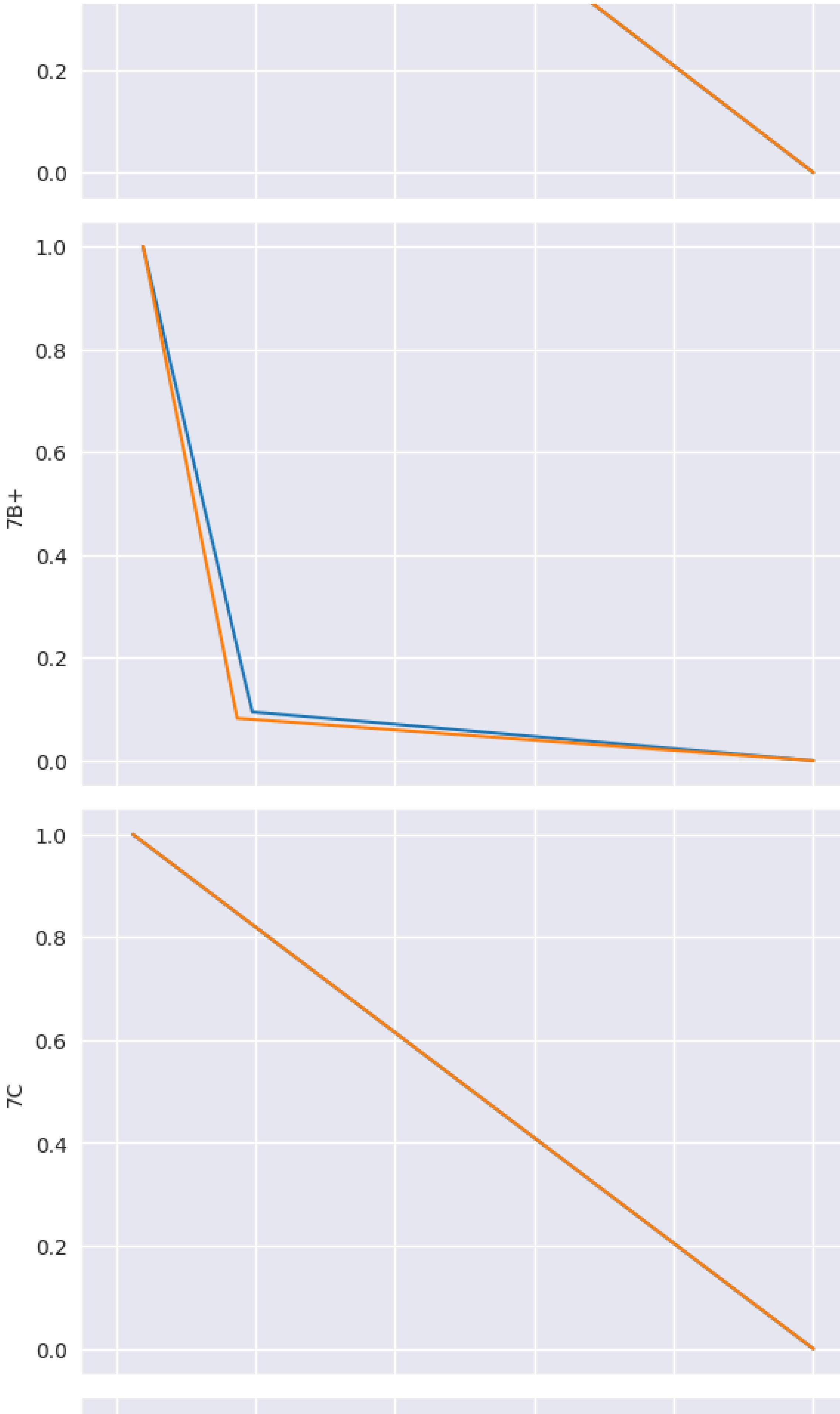


0.6
6A+
0.4
0.2
0.0
1.0
0.8
0.6
6B
0.4
0.2
0.0
1.0
0.8
0.6
6B+
0.4
0.2

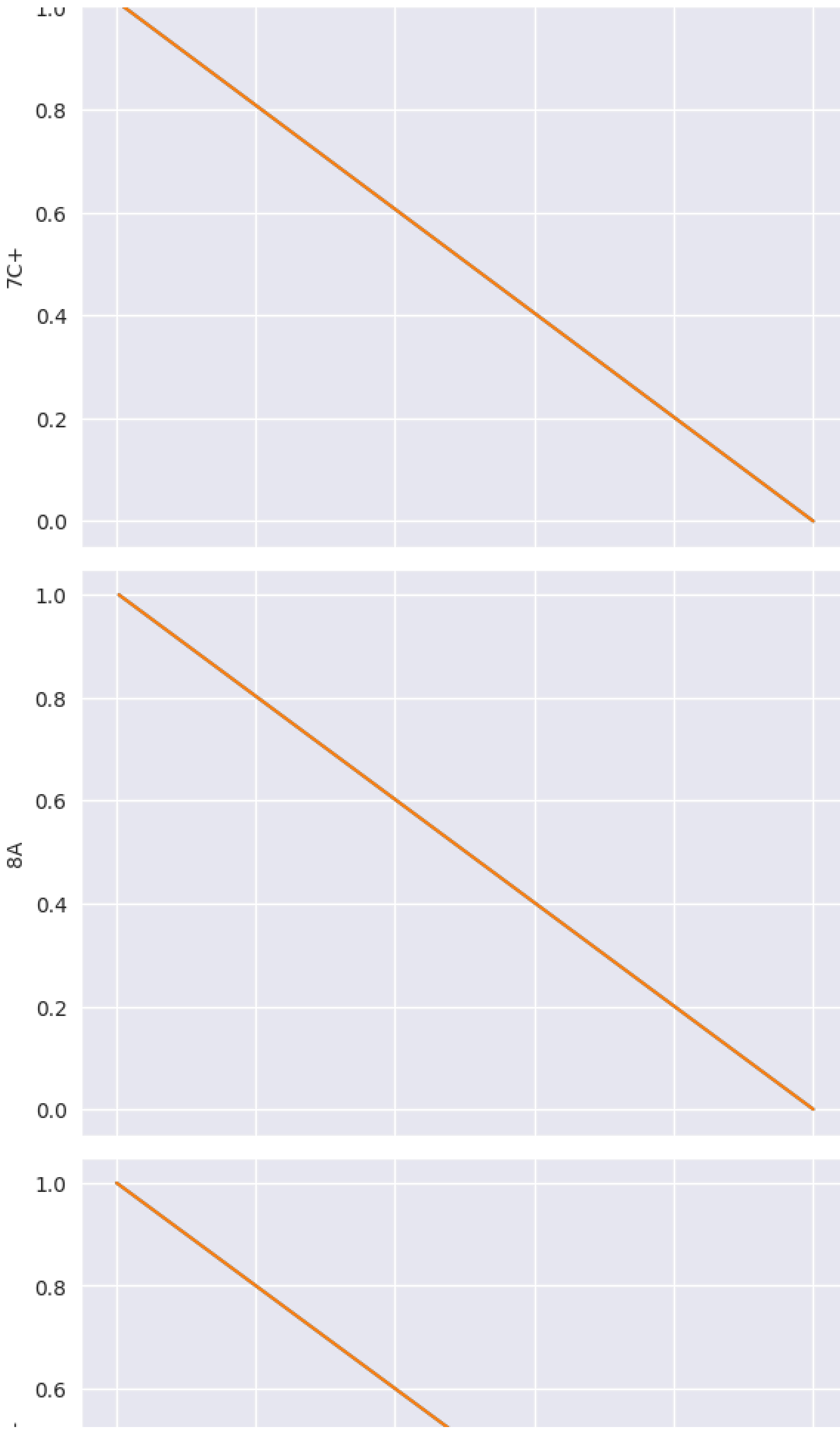

0.0
1.0
0.8
0.6
6C
0.4
0.2
0.0
1.0
0.8
0.6
6C+
0.4
0.2
0.0
1.0



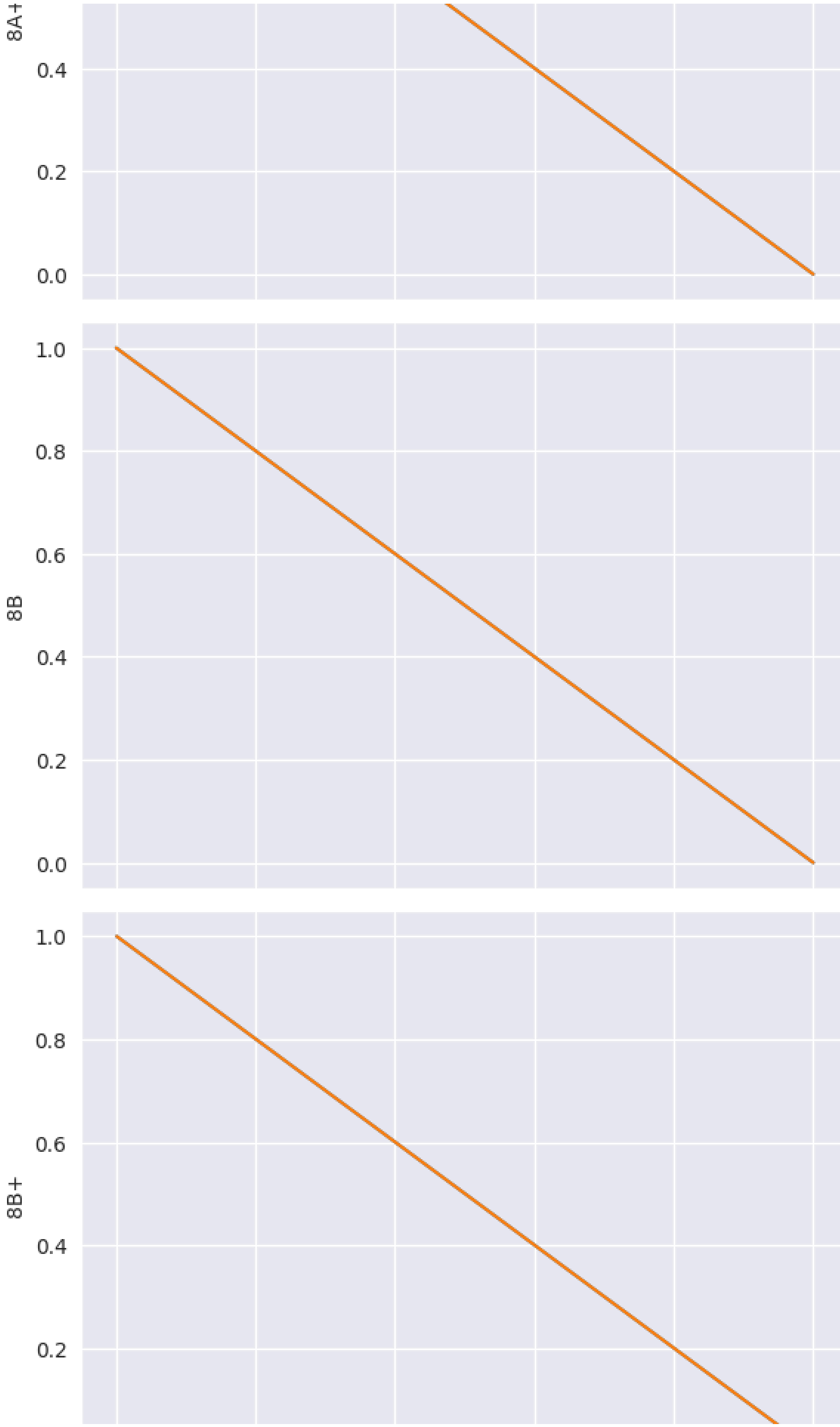
0.8
0.6
7A
0.4
0.2
0.0
1.0
0.8
0.6
7A+
True Positive Rate
0.4
0.2
0.0
1.0
0.8
0.6
7B
0.4

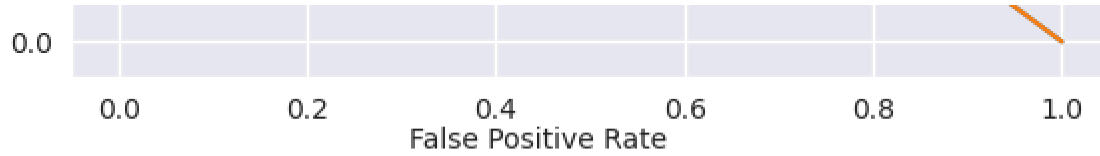


0.2
0.0
1.0
0.8
0.6
7B+
0.4
0.2
0.0
1.0
0.8
0.6
7C
0.4
0.2
0.0



1.0
0.8
0.6
7C+
0.4
0.2
0.0
1.0
0.8
0.6
8A
0.4
0.2
0.0
1.0
0.8
0.6


8A+
0.4
0.2
0.0
8B
1.0
0.8
0.6
0.4
0.2
0.0
8B+
1.0
0.8
0.6
0.4
0.2



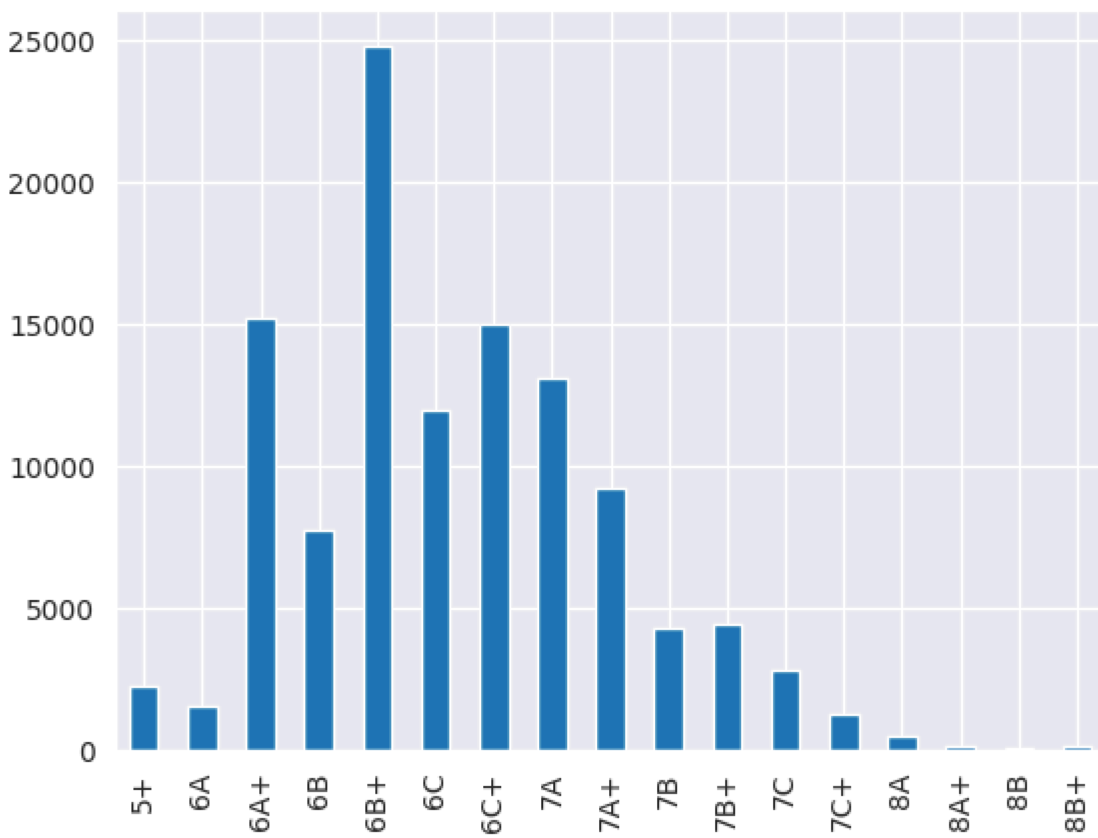
Class weights

We'll use a Keras feature called class weights, that allow our model to take into account class imbalances and adapt its learning.

Here is the distribution of classes in the training dataset:

In [47]:
```
train_labels.sum().plot(kind='bar')
```

Out[47]: <Axes: >



Calculate class weights

In [48]:
```
from sklearn.utils.class_weight import compute_class_weight

class_weights = compute_class_weight(class_weight='balanced', classes=np.ara
class_weight_dict = dict(enumerate(class_weights))
```

Train model

In [ ]:
```
train_model(
  model=compile_model(build_function=create_baseline),
  name='baseline_weighted',
  training_features=[train_moves, train_features],
  training_labels=train_labels,
  class_weight=class_weight_dict,
  epochs=50,
)
```

This weighted training made the model overfit farther than before: the model started to learn some patterns.

Accuracies

In [49]:
```
baseline_weighted, train_predicted, train_y_true, train_y_pred, test_predict
```

```
2024-10-14 18:16:23.425958: W external/local_tsl/tsl/framework/cpu_allocator
_impl.cc:83] Allocation of 68001120 exceeds 10% of free system memory.
2024-10-14 18:16:23.493606: W external/local_tsl/tsl/framework/cpu_allocator
_impl.cc:83] Allocation of 68001120 exceeds 10% of free system memory.
```

In [50]:
```
print_accuracies(baseline_weighted, test_y_true, test_y_pred)
```

```
Accuracy: 28.77%
Balanced Accuracy: 24.13%
Accuracy for Top3: 59.40%
Accuracy for Top5: 78.95%
```

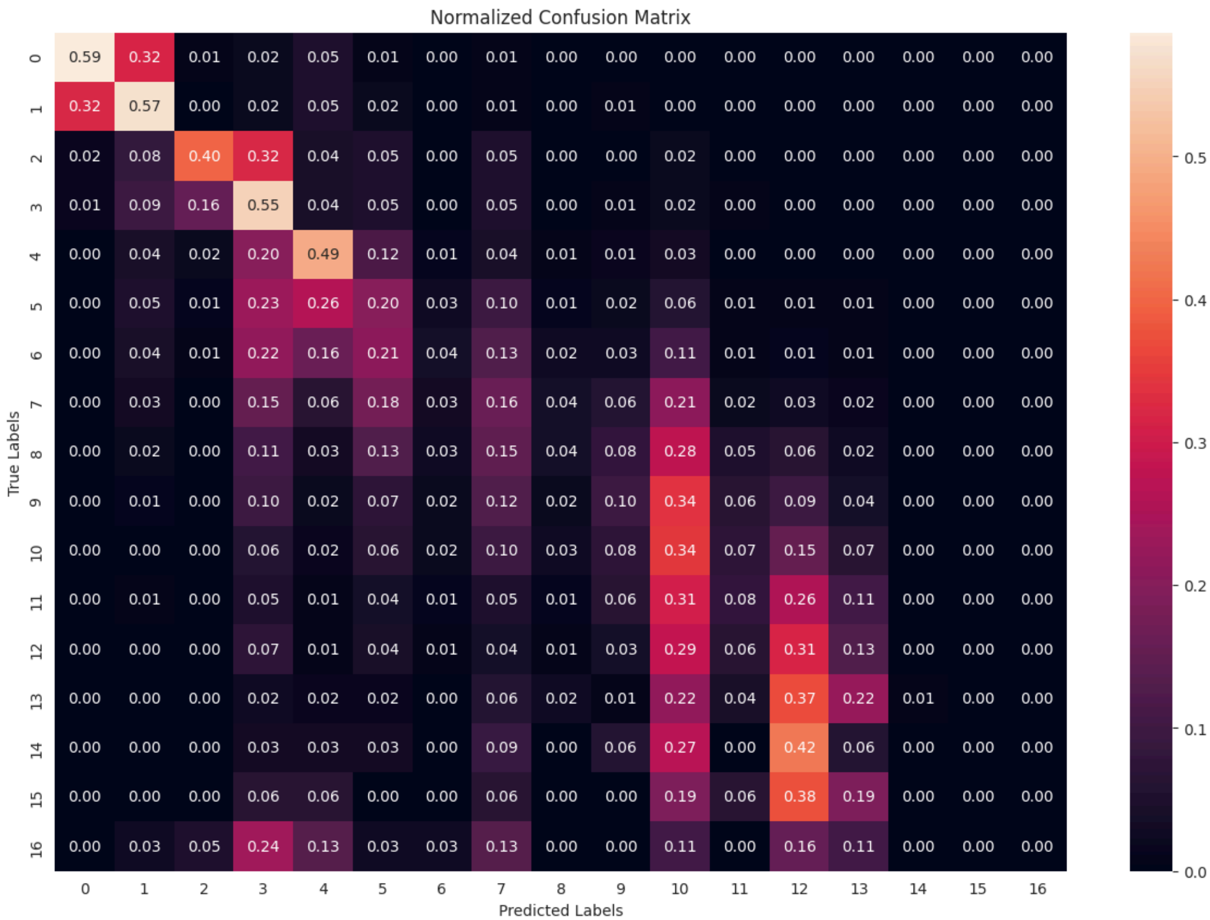
Global accuracies are less important, because they are too precise for our climbing problem.

Here, the balanced accuracy is better, which is a sign of our model generalizing more and not only skipping rare grades.

Confusion matrix

In [51]:
```
confusion_matrix_analysis(test_y_true, test_y_pred)
```

```
Accuracy for grade 5+: 58.67%
Accuracy for grade 6A: 57.26%
Accuracy for grade 6A+: 39.92%
Accuracy for grade 6B: 54.78%
Accuracy for grade 6B+: 49.39%
Accuracy for grade 6C: 20.28%
Accuracy for grade 6C+: 3.69%
Accuracy for grade 7A: 16.42%
Accuracy for grade 7A+: 3.85%
Accuracy for grade 7B: 9.94%
Accuracy for grade 7B+: 34.38%
Accuracy for grade 7C: 7.87%
Accuracy for grade 7C+: 31.43%
Accuracy for grade 8A: 22.40%
Accuracy for grade 8A+: 0.00%
Accuracy for grade 8B: 0.00%
Accuracy for grade 8B+: 0.00%
```



Predictions for easier grades are more concentrated on the diagonal, and our model now predicts difficult grades.

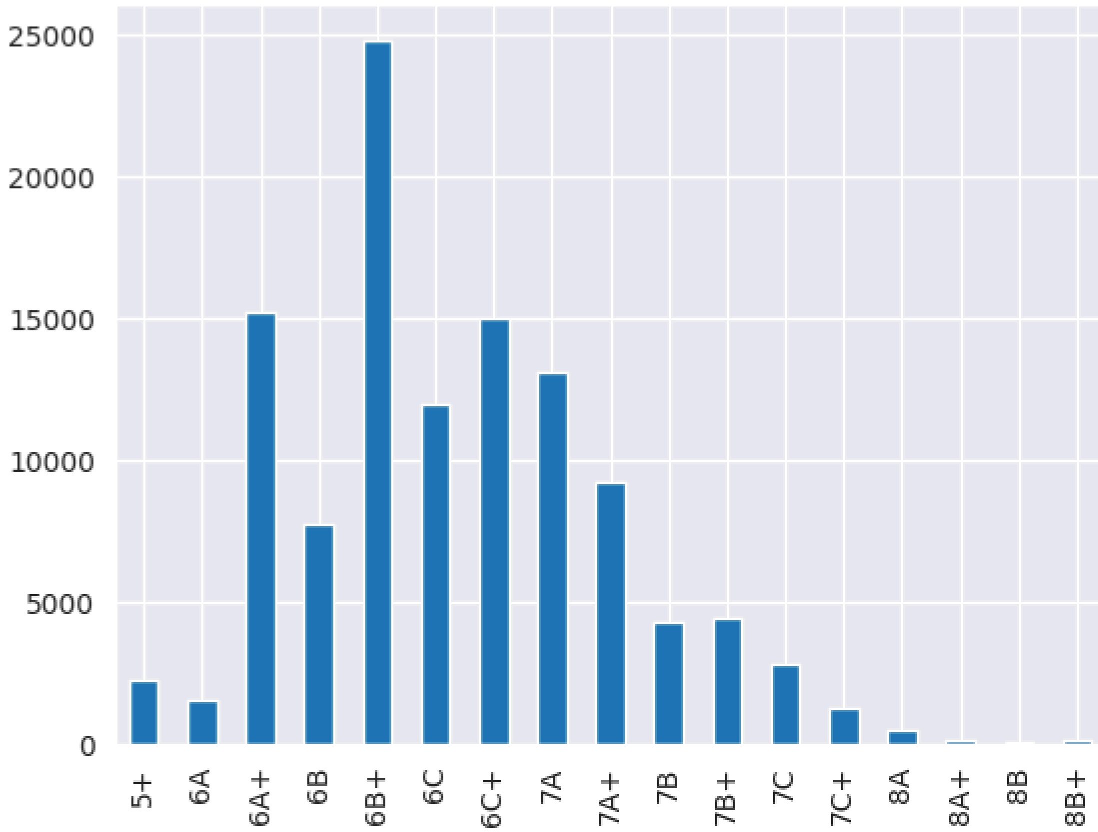
The new problem here is that our model tends to overestimate difficult routes (lower triangle is more filled in the sub-matrix [10:, 10:])

Combine under-sampling and over-sampling

We'll try to keep all counts in range `[10000; 20000]` except for extreme classes (8A and further).

In [52]:
```
train_labels.sum().plot(kind='bar')
```

Out[52]: `<Axes: >`



Under-sampling

In [53]:
```
from imblearn.under_sampling import RandomUnderSampler

under_sampler = RandomUnderSampler(
  sampling_strategy={
    2: 10_000,
    4: 10_000,
    5: 10_000,
    6: 10_000,
    7: 10_000
  }
)
```

```
train_features_undersample, train_labels_undersample = under_sampler.fit_res
train_moves_undersample, _ = under_sampler.fit_resample(train_moves.reshape(
```

Over-sampling

In [55]:
```
from imblearn.over_sampling import SMOTE

over_sampler = SMOTE(sampling_strategy={
  0: 10_000,
  1: 10_000,
  3: 10_000,
  8: 10_000,
  9: 10_000,
  10: 10_000,
  11: 10_000,
  12: 10_000,
  13: 5_000,
  14: 5_000,
  15: 5_000,
  16: 5_000,
})
train_combined_undersample = np.concatenate([train_features_undersample, tra

train_combined_resampled, train_labels_resampled = over_sampler.fit_resample
```

In [56]:
```
train_features_resampled = train_combined_resampled[:, :nb_features]
train_moves_resampled = train_combined_resampled[:, nb_features:].reshape(-1
```

In [57]:
```
train_labels_resampled.sum(axis=0)
```

Out[57]:
```
array([10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000, 10000,
       10000, 10000, 10000, 10000,  5000,  5000,  5000,  5000])
```

Model training

In [ ]:
```
train_model(
  model=compile_model(build_function=create_baseline),
  name='baseline_resampled',
  training_features=[train_moves_resampled, train_features_resampled],
  training_labels=train_labels_resampled,
  epochs=50,
)
```

The training accuracy is the best of all, but the validation accuracy is the worst of all... training and validation lost curves keep the same distance for every epoch but with an important gap

Treating routes as images: Convolution

During Data analysis, we chose to plot our routes as images, with the three separate channels representing the type of hold (start, middle, end). So, if our routes can be interpreted as images, why can't our problem be an image classification problem? That's what we will explore using Convolutional Neural Networks (CNN).

Testing multiple configurations

Here, we try several different configurations using many techniques :

- Conv2D vs SeparableConv2D layers
- Number and shape of layers
- Padding, strides
- Residual connections
- Normalization in the middle of the model

In [58]:
```
def create_convolutional():
  shape = [32, 64, 128, 256]

  moves_inputs = keras.Input(shape=MOVES_SHAPE, name="moves")
  features_inputs = keras.Input(shape=(nb_features,), name="features")

  x = keras.layers.Dense(64, activation='relu')(features_inputs)
  features_outputs = keras.layers.Dense(64, activation='relu')(x)

  # The assumption for using depth wise-separable convolution is channel inc
  # The three channels are part of the same route, and only indicate the sta
  y = keras.layers.Conv2D(filters=32, kernel_size=3, padding='same', use_bia

  for i, filters in enumerate(shape):
    connection = y

    y = tf.keras.layers.BatchNormalization()(y)
    y = tf.keras.layers.Activation('relu')(y)
    y = keras.layers.SeparableConv2D(filters=filters, kernel_size=3, padding

    y = keras.layers.MaxPool2D(pool_size=2, padding='same')(y)

    # Residual connection fit
    connection = keras.layers.Conv2D(filters=filters, kernel_size=1, strides

    y = keras.layers.add((y, connection))

  moves_outputs = keras.layers.GlobalAveragePooling2D()(y)

  x = keras.layers.concatenate([features_outputs, moves_outputs])

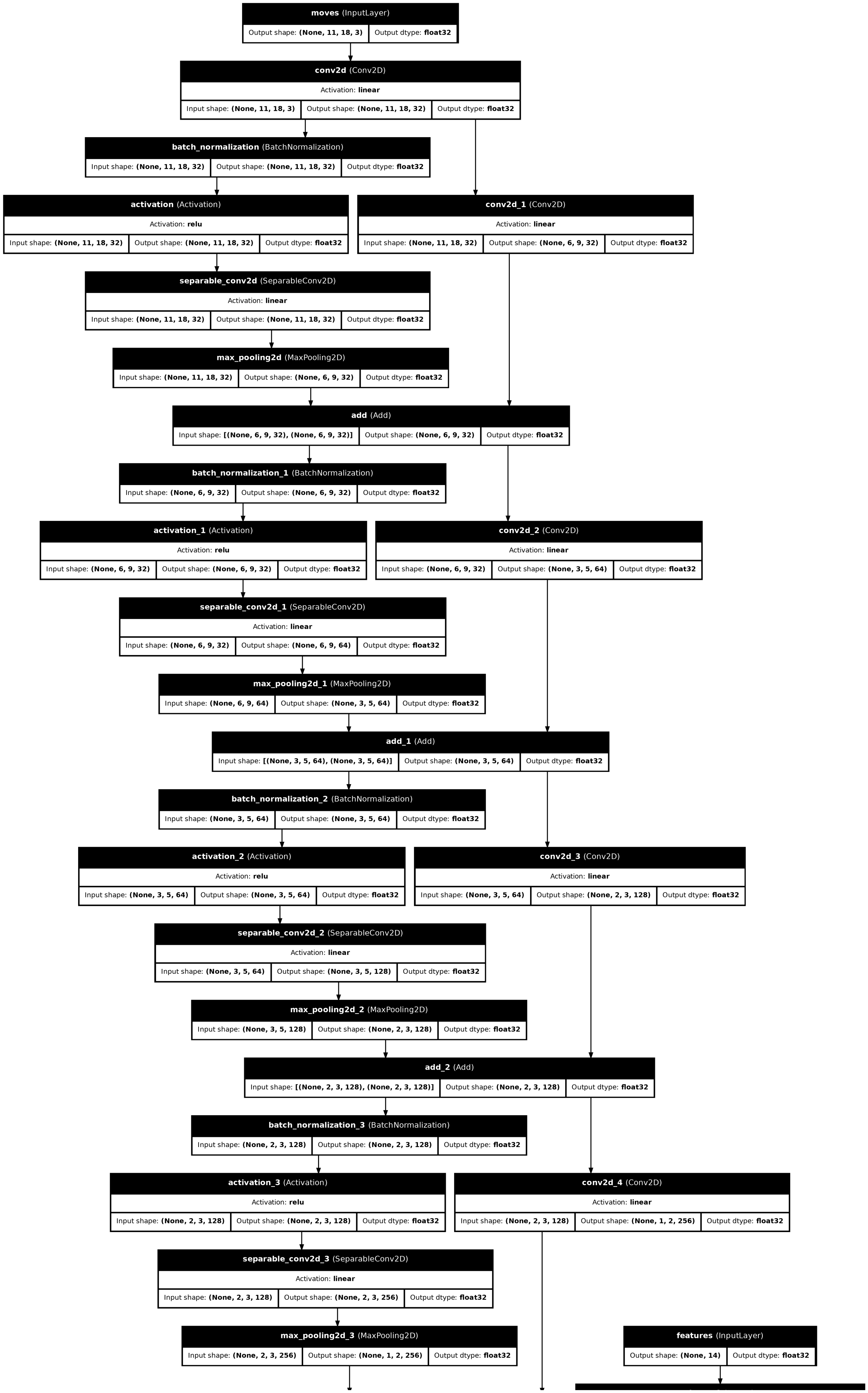
  x = keras.layers.Dense(64, activation='relu')(x)
  x = keras.layers.Dropout(0.5)(x)
  outputs = keras.layers.Dense(nb_labels, activation='softmax')(x)
```

```
    return keras.Model(inputs=[moves_inputs, features_inputs], outputs=outputs
```

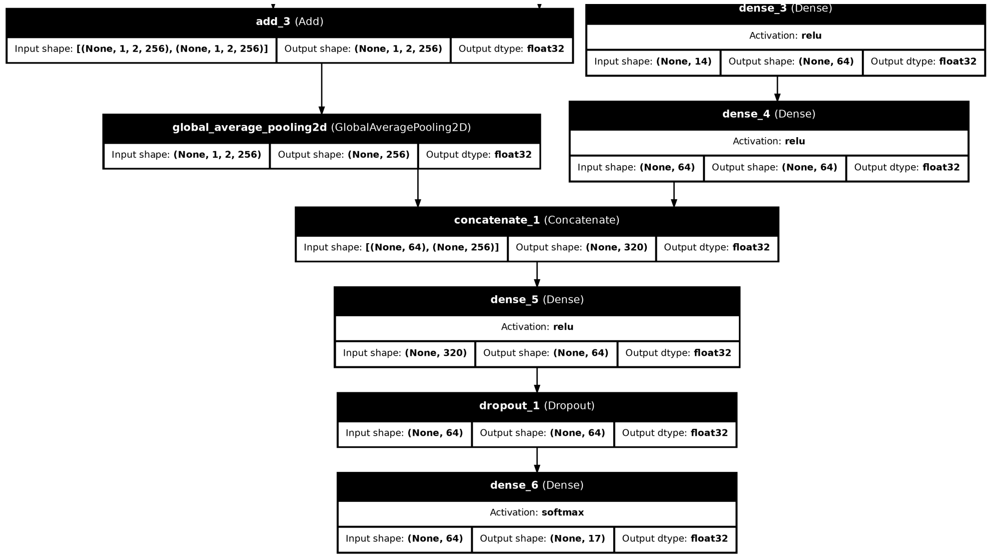
In [59]:
```
convolution_model = compile_model(build_function=create_convolutional)
```

In [60]:
```
plot_model(convolution_model)
Image('model.png')
```

Out[60]:



moves (InputLayer)
Output shape: (None, 11, 18, 3)
Output dtype: float32
conv2d (Conv2D)
Activation: linear
Input shape: (None, 11, 18, 3)
Output shape: (None, 11, 18, 32)
Output dtype: float32
batch_normalization (BatchNormalization)
Input shape: (None, 11, 18, 32)
Output shape: (None, 11, 18, 32)
Output dtype: float32
activation (Activation)
Activation: relu
Input shape: (None, 11, 18, 32)
Output shape: (None, 11, 18, 32)
Output dtype: float32
conv2d_1 (Conv2D)
Activation: linear
Input shape: (None, 11, 18, 32)
Output shape: (None, 6, 9, 32)
Output dtype: float32
separable_conv2d (SeparableConv2D)
Activation: linear
Input shape: (None, 11, 18, 32)
Output shape: (None, 11, 18, 32)
Output dtype: float32
max_pooling2d (MaxPooling2D)
Input shape: (None, 11, 18, 32)
Output shape: (None, 6, 9, 32)
Output dtype: float32
add (Add)
Input shape: [(None, 6, 9, 32), (None, 6, 9, 32)]
Output shape: (None, 6, 9, 32)
Output dtype: float32
batch_normalization_1 (BatchNormalization)
Input shape: (None, 6, 9, 32)
Output shape: (None, 6, 9, 32)
Output dtype: float32
activation_1 (Activation)
Activation: relu
Input shape: (None, 6, 9, 32)
Output shape: (None, 6, 9, 32)
Output dtype: float32
conv2d_2 (Conv2D)
Activation: linear
Input shape: (None, 6, 9, 32)
Output shape: (None, 3, 5, 64)
Output dtype: float32
separable_conv2d_1 (SeparableConv2D)
Activation: linear
Input shape: (None, 6, 9, 32)
Output shape: (None, 6, 9, 64)
Output dtype: float32
max_pooling2d_1 (MaxPooling2D)
Input shape: (None, 6, 9, 64)
Output shape: (None, 3, 5, 64)
Output dtype: float32
add_1 (Add)
Input shape: [(None, 3, 5, 64), (None, 3, 5, 64)]
Output shape: (None, 3, 5, 64)
Output dtype: float32
batch_normalization_2 (BatchNormalization)
Input shape: (None, 3, 5, 64)
Output shape: (None, 3, 5, 64)
Output dtype: float32
activation_2 (Activation)
Activation: relu
Input shape: (None, 3, 5, 64)
Output shape: (None, 3, 5, 64)
Output dtype: float32
conv2d_3 (Conv2D)
Activation: linear
Input shape: (None, 3, 5, 64)
Output shape: (None, 2, 3, 128)
Output dtype: float32
separable_conv2d_2 (SeparableConv2D)
Activation: linear
Input shape: (None, 3, 5, 64)
Output shape: (None, 3, 5, 128)
Output dtype: float32
max_pooling2d_2 (MaxPooling2D)
Input shape: (None, 3, 5, 128)
Output shape: (None, 2, 3, 128)
Output dtype: float32
add_2 (Add)
Input shape: [(None, 2, 3, 128), (None, 2, 3, 128)]
Output shape: (None, 2, 3, 128)
Output dtype: float32
batch_normalization_3 (BatchNormalization)
Input shape: (None, 2, 3, 128)
Output shape: (None, 2, 3, 128)
Output dtype: float32
activation_3 (Activation)
Activation: relu
Input shape: (None, 2, 3, 128)
Output shape: (None, 2, 3, 128)
Output dtype: float32
conv2d_4 (Conv2D)
Activation: linear
Input shape: (None, 2, 3, 128)
Output shape: (None, 1, 2, 256)
Output dtype: float32
separable_conv2d_3 (SeparableConv2D)
Activation: linear
Input shape: (None, 2, 3, 128)
Output shape: (None, 2, 3, 256)
Output dtype: float32
max_pooling2d_3 (MaxPooling2D)
Input shape: (None, 2, 3, 256)
Output shape: (None, 1, 2, 256)
Output dtype: float32
features (InputLayer)
Output shape: (None, 14)
Output dtype: float32



In [ ]:
```
train_model(
  model=convolution_model,
  name='convolution',
  training_features=[train_moves, train_features],
  training_labels=train_labels,
  epochs=70
)
```

Observations

- Overfitting is far away, many epochs can be achieved
- Padding don't cause underfitting, but augmenting the end dense network yes
- Better performances by normalizing after layers and adding residual connections

Using a learning rate schedule

In [ ]:
```
convolution_model = compile_model(build_function=create_convolutional, learn
train_model(
  model=convolution_model,
  name='convolution-schedule',
  # class_weight=class_weight_dict,
  callbacks=[
    keras.callbacks.ReduceLROnPlateau(
      monitor="val_loss",
      factor=0.4,
      patience=2,
      min_lr=1e-6
    )
  ],
  training_features=[train_moves, train_features],
  training_labels=train_labels,
  epochs=70
)
```

Observations

- Slightly better performance when reducing the learning rate to 1e-4
- Reduce LR on plateau: only efficient on training validation, as the LR starts to reduce when the model is overfitting
- 1e-7 is too low: the loss is not decreasing

Conclusion: for this problem, a constant learning rate seems to be the most efficient method

Accuracies

In [61]:
```
best_convolution, train_predicted, train_y_true, train_y_pred, test_predicte
```

```
2024-10-14 18:17:35.495197: W external/local_tsl/tsl/framework/cpu_allocator
_impl.cc:83] Allocation of 68001120 exceeds 10% of free system memory.
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W0000 00:00:1728922668.098547   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.102283   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922668.104899   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922668.108076   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.122889   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922668.125119   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922668.139209   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.146255   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.213114   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.215242   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.296567   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.298677   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922668.301989   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.412331   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922668.414407   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.267829   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.315376   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.337658   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.341652   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.343726   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.345806   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.349943   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.352083   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922672.647913   38573 gpu_timer.cc:114] Skipping the delay k
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```

In [62]:
```
print_accuracies(best_convolution, test_y_true, test_y_pred)
```

```
Accuracy: 40.26%
Balanced Accuracy: 23.08%
Accuracy for Top3: 76.43%
Accuracy for Top5: 92.03%
```

Overall accuracy is the best so far, but balanced accuracy is worse than with class weights. We can add this last technique to further improve our model.

Explainability

We now try to explain the results of our model, by using Shap and visualisation techniques. These last work well with Convolutional Neural Network to plot the filters and get an insight of what's happening.

Features importance

In [63]:
```
import shap

explainer = shap.GradientExplainer(best_convolution, [train_moves, train_fea

# Shape of shap_values
# - First element: (nb_samples, WIDTH, HEIGHT, CHANNELS, nb_outputs)
# - Second element: (nb_samples, nb_features, nb_labels)
shap_values = explainer.shap_values([test_moves[:4], test_features.values[:4
```

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W0000 00:00:1728922678.931543   38365 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922678.934998   38365 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922679.873049   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922679.884289   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.890677   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.894176   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.898551   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922679.904361   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.907135   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.909259   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.911385   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.913655   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.919802   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.922736   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.924972   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.927174   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.929543   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.931747   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.933960   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.937562   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.945834   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.947982   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.950100   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.952183   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922679.954300   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922679.956555   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.958700   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.960854   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.963054   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.965216   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.967403   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.969892   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.972085   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.974255   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.976514   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922679.985612   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.988993   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.991718   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922679.994047   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922679.996603   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.002746   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.005920   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.008997   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.012219   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.020459   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.024602   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.027416   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.037605   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.045424   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.052089   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.057044   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.060523   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.072106   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.075515   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.078369   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.081325   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.086268   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.091420   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.094009   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.097333   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.099672   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.107054   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.110283   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922680.112590   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.116611   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.123076   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.125834   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.138890   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.141904   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.146822   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.149633   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.154739   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.158182   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.160919   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.164210   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.166737   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.170148   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.174862   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.177060   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922680.185037   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.187358   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.191508   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.203884   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.207010   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.211125   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.215701   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.220432   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.224669   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.228162   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.230774   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.235604   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.238790   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.243604   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.246484   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.248924   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.253943   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.257534   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.266462   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.272200   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.275924   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.278392   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.285699   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.296226   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.298473   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.304804   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.309424   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.311868   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.314043   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.316832   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.321942   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.326767   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.329624   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.332590   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.443338   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.472403   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.476078   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.548558   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.615518   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922680.620419   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.623888   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.628476   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.632434   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.639189   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.644182   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.649279   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.670024   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.672982   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.675237   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.679754   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.685879   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.688928   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.691740   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.694019   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.696136   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.698408   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.701386   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.704360   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.708440   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.710852   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.713009   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.716126   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.724583   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.726757   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.728922   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.731103   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.733284   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
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W0000 00:00:1728922680.736457   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.738793   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.741179   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.744893   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.747094   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.749318   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.752123   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.757194   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.759422   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.761624   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.763968   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.765986   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.768158   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.770548   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.773246   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.779726   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.782140   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.784394   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.786721   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.789025   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.791520   38573 gpu_timer.cc:114] Skipping the delay k
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W0000 00:00:1728922680.793657   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.795819   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.798289   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
W0000 00:00:1728922680.800801   38573 gpu_timer.cc:114] Skipping the delay k
ernel, measurement accuracy will be reduced
```

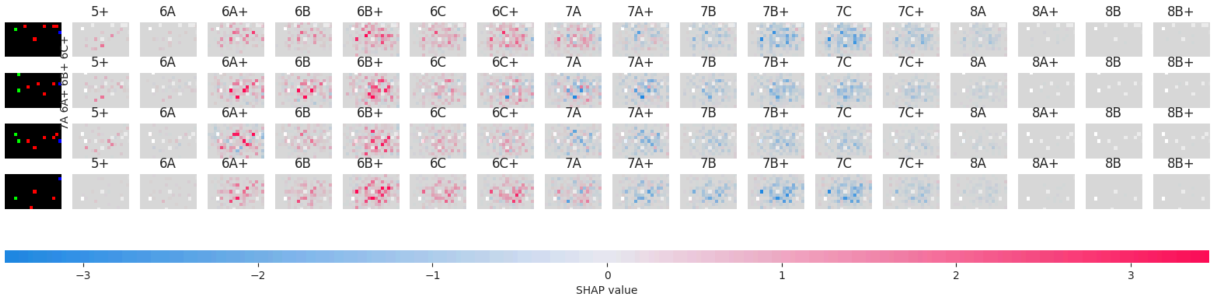
In [64]:

```python
plt.figure(figsize=(60, 10))
shap.image_plot(
  [shap_values[0][:, :, :, :, i] for i in range(nb_labels)],
  test_moves[:4] * 255,
  labels=np.tile(all_grades, (nb_labels, 1)),
```

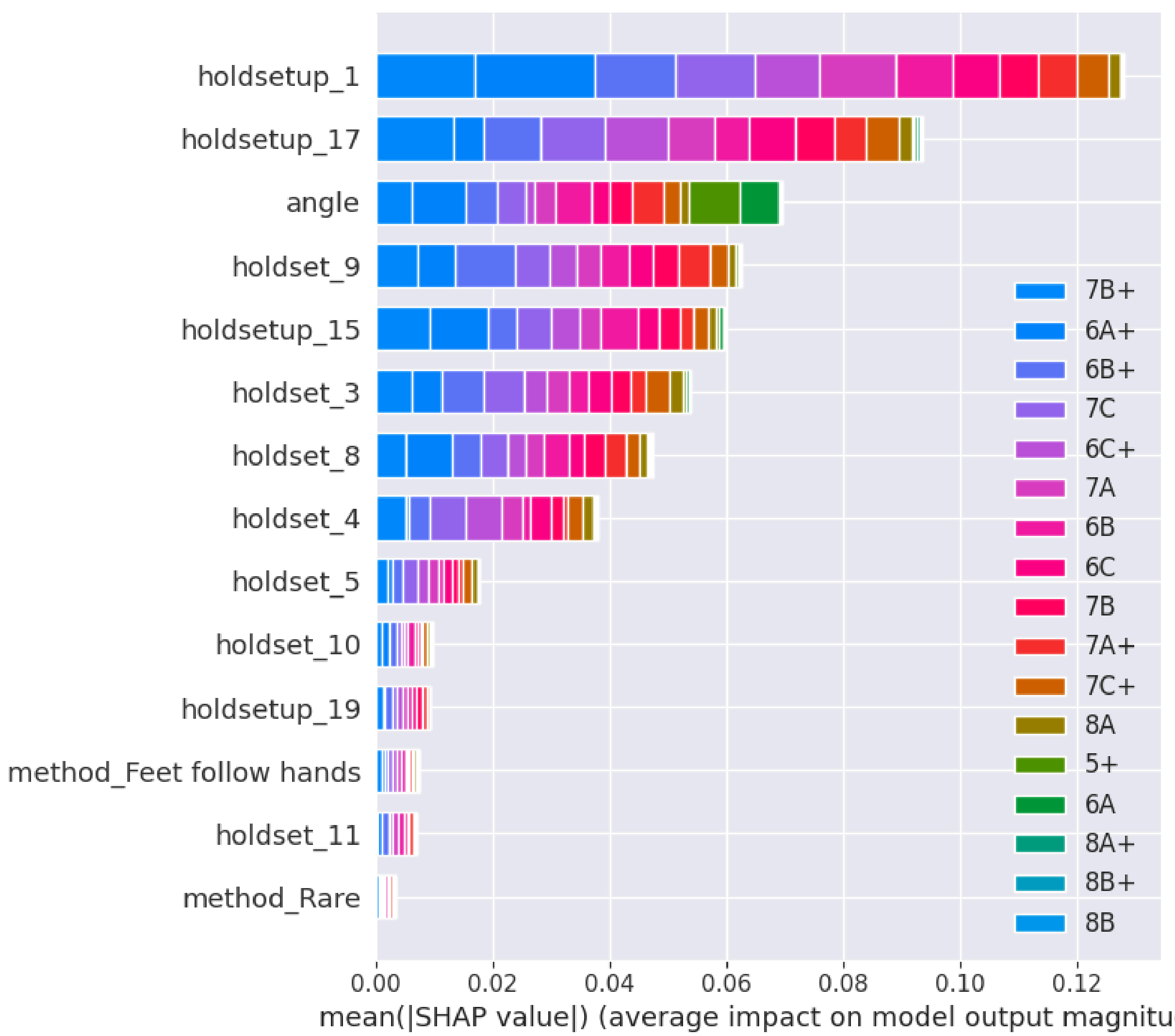
```
    show=False
)
plt.text(-350, -30, ' '.join(np.vectorize(lambda i: all_grades[i])(np.flip(t
```

Out[64]: Text(-350, -30, '7A 6A+ 6B+ 6C+')

<Figure size 6000x1000 with 0 Axes>



In [65]:
```
shap.summary_plot(
    [shap_values[1][:, :, i] for i in range(nb_labels)],
    plot_type='bar',
    class_names=all_grades,
    feature_names=features.columns
)
```



- Board angle has the most influence on the grade, as it's more difficult to climb a steep route. It has almost an equal importance for all grades, if we take into account class imbalance
- Method has the least influence: not fully using feet doesn't make the route more difficult ; it's likely to be due to strong angles on moonboards (25° and 40°), thus the majority of the effort done by the climber is located in the arms and chest

Filters visualisation (TODO)

Conclusions

The conclusion will be written when the project has been completed, so after testing different configurations to reach the best performances, as well as explaining these results. Stay tuned!