

STUTTGART MEDIA UNIVERSITY

MASTER THESIS

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**Applied Research of an End-to-End  
Human Keypoint Detection Network with  
Figure Ice Skating as Application Scope**

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*A thesis submitted in fulfillment of the requirements  
for the degree*

**Master of Science**

**Computer Science and Media**

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# Declaration of Authorship

I, Nadin-Katrin APEL, declare that this thesis titled, “Applied Research of an End-to-End Human Keypoint Detection Network with Figure Ice Skating as Application Scope” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at
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- Where I have consulted the published work of others, this is always clearly attributed.
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- quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was
- done by others and what I have contributed myself.

Signed:

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Date:

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*“Data is a precious thing and will last longer than the systems themselves.”*

Tim Berners-Lee



STUTTGART MEDIA UNIVERSITY

# *Abstract*

Computer Science and Media

Master of Science

## **Applied Research of an End-to-End Human Keypoint Detection Network with Figure Ice Skating as Application Scope**

by Nadin-Katrin APEL

Human joint detection is a key component for machines to understand human actions and behaviors. Especially in figure ice skating this understanding is an indispensability, where there are many difficult figures and poses, even difficult to clearly understand for the professionalized jury. Herewith we present an end-to-end approach to detect the 2D poses of a person in images and videos. In the architecture we combine three branches: Image Segmentation, Body Part Detection, and Human joint detection. The applied research reveals multiple findings which outperform current existing main players with the special application scope of figure ice skating.





## *Acknowledgements*

The acknowledgments and the people to thank go here, don't forget to include your project advisor



# Contents

<b>Declaration of Authorship</b>	<b>iii</b>
<b>Abstract</b>	<b>vii</b>
<b>Acknowledgements</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation and Goals . . . . .	2
1.2 Related Work . . . . .	3
<b>2 Figure Skating Pose Detection</b>	<b>7</b>
2.1 Complexity of Figures . . . . .	7
2.2 Distinct Rating System . . . . .	8
<b>3 Dataset</b>	<b>11</b>
3.1 Figure Skating Dataset . . . . .	11
3.1.1 Motion capturing techniques . . . . .	11
3.1.2 XSens: Inertial motion capturing recordings on the ice rink . . .	12
3.2 Synthetic Dataset: 3DPeople . . . . .	15
3.3 Data Processing . . . . .	16
<b>4 Method</b>	<b>19</b>
4.1 Training Performance (human parts) . . . . .	21
4.2 Inference Runtime Analysis . . . . .	22
4.3 Implementation Details . . . . .	23
<b>5 Experiments</b>	<b>25</b>
5.1 Ablation Study . . . . .	25
5.1.1 Body Parts Detection Module . . . . .	25
5.1.2 Joint Detection Module . . . . .	30
5.2 Comparison of Optimizer Algorithms . . . . .	34
5.2.1 Experiments with optimizers . . . . .	40
5.3 Performance of loss functions . . . . .	42
5.3.1 Commonly used loss functions . . . . .	42
5.3.2 Our custom loss function CILoss . . . . .	44
<b>6 Conclusion and future thoughts</b>	<b>47</b>
<b>Bibliography</b>	<b>51</b>



# List of Figures

3.1	3DPeople . . . . .	15
4.1	HRNetV3 . . . . .	19
4.2	Alena step . . . . .	20
4.3	Alena step . . . . .	22
4.4	Alena step . . . . .	22
5.1	Ablation Human Parts Module: Accuracy . . . . .	28
5.2	Ablation Human Parts Module: Correct Pixel . . . . .	28
5.3	Ablation Human Parts Module: Correctness Ratio . . . . .	29
5.4	Ablation Human Parts Module: 1st Episode Predictions . . . . .	29
5.5	Ablation Human Parts Module: 20th Episode Predictions . . . . .	30
5.6	Ablation Keypoints Detection Module: Predicted Training Images . . .	32
5.7	Ablation Keypoints Detection Module: Predicted Training Images . . .	33
5.8	Ablation Keypoints Detection Module: Predicted Training Images . . .	33
5.9	HRNetV3: Predicted Feature Maps . . . . .	34
5.10	Learning Rate SGD . . . . .	40
5.11	Accuracy . . . . .	41
5.12	loss . . . . .	41
5.13	SCCE: Accuracy . . . . .	44
5.14	SCCE: predictions . . . . .	44
5.15	CILoss . . . . .	45



# List of Tables

5.1 Ablation Human Parts Module . . . . .	26
5.2 Ablation Keypoint Module . . . . .	30





# List of Abbreviations

**LAH** List Abbreviations **Here**  
**WSF** What (it) Stands **For**



# Physical Constants

use it Speed of Light  $c_0 = 2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$  (exact)



# List of Symbols

$a$	distance	m
$P$	power	W (J s <sup>-1</sup> )
$\omega$	angular frequency	rad



*For/Dedicated to/To my...*





## Chapter 1

# Introduction

Human 2D pose estimation has gained more and more attraction in recent years. For example, *Facebook*, one of the BigFive technology companies, has published 73 research paper targeting the problem of pose estimation in the last three years. The most popular ones are *DensePose*, *VideoPose3d* or *Mask R-CNN* [2, 16, 20, 36]. A company in Canada *wrnrch.ai* even specialized on keypoint recognition from image and video data with a lot of product options [63]. Furthermore, many enterprises are becoming more and more interested in Sports Content Analysis (SPA) e.g. *Bloomberg*, *SAP*, and *Panasonic*, just naming a few [14, 44].

But how got this topic into such a demanded focal point? Probably this is due to the various application areas to which Pose estimation can be applied to. Main fields are sports, visual surveillance, autonomous driving, entertainment, health care and robotics [35, 49, 68]. For example *Vaak*, a Japanese startup, developed a software, which would detect shoplifters, even before they were able to remove items from a store. This yielded in a drastic reduction in stealing crimes in stores [53].

The exercise of sport not via visiting a sports course, gym or club became of fundamental severance in 2020, when the Coronavirus SARS-CoV-2 spread the entire world [41]. Many courses such as Yoga, Pilates, or general fitness routines went online and were often conducted via Zoom, Instagram Live, or other video streaming technologies [3]. However, what participants were often missing, was the feedback of the coach on how the exercise was going, and whether it was done right or wrong. So in 2020 more than ever was missed a technology, which is good at pose estimation, or even further, action recognition, in sports.

Most investigations in this field target usual activities not including complex poses, which can be encountered in professional sports. This is why these architectures often fail when applied to more complex movements. For competitive sports, there are various metrics of high interest depending on the environment. Competition and training can be differentiated as can be sports executed by multiple athletes versus single combats. Basketball or soccer as team sports, for example, are interested in predictions about how the other team behaves during the game and which would be the best reaction to their behavior for winning the game. During practice, 2d pose recognition can help to optimize the sports-person movements by taking the role of a coach. This could provide an answer to the question on how certain activities might be optimized.

Single competitive sports with very complex movement routines are for example gymnastics and figure ice skating. Both sports include various artistic body movements, which are not part of daily activities. Even famous and well-rated 2d pose recognition networks such as *OpenPose* or *VideoPose3d* fail to recognize these poses.

If this problem was solved, it could help with action recognition and support during practice or relieve the jury on competitions. A predictor could for example suggest, what an athlete should do to land a certain jump. On the other hand, jury is rare and the job sitting all day in the ice-rink on weekends with only a very small salary is not very attractive. In fact, people often complain scoring is not executed fairly [29, 54, 55].

Especially in figure ice skating an accurate 2d pose recognition module could make a huge contribution. This is why this paper investigates 2d pose recognition with a special focus on figure ice skating.

## 1.1 Motivation and Goals

A working 2d pose estimator could make a huge contribution to figure ice skating. Especially when building an action recognizer on top of it. However, as of today, this was not possible yet due to the complex poses and the different gliding movements on the ice. Indeed, spins with their fast rotation and stretching poses are of high complexity to these estimators. Such an estimator could support fair scoring

during competitions or help to improve motion sequences during practice.

With the downward trend of jury staff and the increasing demand for more small competitions, the jury is asked more and more in figure ice skating. Particularly the role of the technical specialist or controller diagnosing the individual elements on the ice is of high demand. In recent years, some competitions were even canceled, because they were not able to find the inevitable jury. In addition, sitting all day in the cold ice rink for only a very low salary is not attractive at all. These long demanding days challenge concentration and many competition participants often complain about jury not rating fairly enough, completely forgetting the demanding work the jury has to do. Here a 2d pose estimator could contribute by recognizing the different elements or even scoring. This would not only relieve the jury but also could increase fairness.

During practice, 2d pose estimators could examine the specific motions during elements and give hints on how to improve these. Probably they could even suggest certain exercises to learn an element like a spin, jump, or certain step. Additionally, they could keep track of training and provide analysis metrics to the skaters and coaches.

All in all, 2d pose estimation is very interesting not only because of all the possible different appliance possibilities in this sport, but as well because of the challenging task to build an appropriate estimator, which was not possible until today.

## 1.2 Related Work

2D Pose estimation sets the baseline for machines to understand actions. It is the problem of localizing human joints or keypoints in images and videos. Many research studies explored and researched this topic already with the most popular ones being *OpenPose* and *VideoPose3d* [5, 36].

For 2D pose recognition there are mainly two general procedures: either *top-down* or *bottom-up*. *Top-down* first detects a person and then finds their keypoints. Whereas *bottom-up* first detects all keypoints in the image and then refers to the corresponding

people. For top-down it is argued, that if a person is not detected via a bounding-box or alike, no keypoints can be found. This would lead to more undetected keypoints in the frames of a video. When there are many people in the image with many occlusions, people often can not be detected. However, when a person is correctly detected, it is said that accuracy would be higher [34].

A famous *top-down* approach for example is *Mask R-CNN* developed by the *Facebook AI Research* team. It consists of three branches and two stages. The first stage presents the *Region Proposal Network (RPN)*. It proposes candidate bounding-boxes for objects. The second stage performs classification and bounding-box regression by extracting features using region of interest pooling, which they refer to as *RoiPool*. Additionally, *Mask R-CNN* predicts a binary mask for each *ROI* in the second stage. They receive top results in the *COCO* challenges for instance segmentation, bounding-box object detection, and person keypoint detection [16]. Other famous *top-down* approaches include *Simple Baselines*, the *Cascaded Pyramid Network* or *Deep High-Resolution Learning* [8, 50, 64].

One of the most discussed and popular *bottom-up* approaches as of today is *OpenPose*. Their net predicts vector fields for the joint connections, which they call *Part Affinity Fields (PAF)*. Additionally, it estimates candidate keypoint locations via Gaussian distributions. These they refer to as *Part Confidence Maps*. From these detections, they refer to the associated human poses. *OpenPose* shows very good results on the *MPII* and *COCO* challenges. They highlight their performance, which especially shows it's strength when detecting multiple people. The performance wouldn't change even if more and more people enter the scene. With sufficient hardware equipment, this would even show decent results in realtime [5].

In a newer research, they additionally pay attention to the temporal characteristic in video sequences in their work of *Spatio Temporal Fields*. Their approach is able to track multiple people's poses across frames being runtime-invariant to the number of people in the frames. Besides, they receive highly competitive results on the *PoseTrack* challenges [39]. Some other famous *bottom-up* approaches include *Convolutional Pose Machines* and *PifPaf* [24, 62].

The COCO, MPII and PoseTrack challenges lead to several studies in the pose estimation field. Nevertheless, their dataset targets rather simple daily activities. There have been only conducted a few studies on competitive sports such as basketball, ice-hockey or swimming [13, 34, 60]. For sports including full-body flexibility or special unconventional jump or turn rotations as can be found in dance, gymnastics or figure ice skating, there have been only a few studies [6, 25, 66, 67].

Studies on figure ice skating topics encounter three main problems: The first is domain knowledge. In C. Xu et Al.'s research, they try to predict the technical and performance scores from video data with the only the ice skating program as video input and the judge scores as labels [66]. This will very likely not result in useful results since first, the figure ice skating judging system adjusts every year, second, there are always different judges on the competitions who all have their own rating style, and third however, the skater is one of the always winning ones, this skater can do a good program falling at the main elements and still score very well, because the jury knows this skater and is just human in their judgment. This is one of the main controversies in the figure ice skating fairness of program judgment. Another problem is the missing dataset. There didn't exist a dataset with joint labeling until FSD-10 [25], which only came out at the beginning of the year. One very interesting study from Yu, Ri et Al. tries to create simulations from the figure ice skating elements. They exactly encountered the problem, that pose estimation currently does not work on difficult pose sequences such as spins or very flexible positions. However, they were able to successfully predict jumps and simple steps from videos into 3d simulation [64].

## Goals

Our goal was to find a way on how to detect human poses in single figure ice skating, with an architecture, which would even be possible to run on devices with lower computation power such as mobile phones. Important is, that only the main character in the image should be detected, and all background people would be neglected, so our network could later be used for action recognition and recommendation tasks during practice when there are multiple skaters on the ice.

## Our Work

In our work we tested the performance of *VideoPose3d*, *OpenPose*, and *wrnch.ai* on figure ice skating elements, with the outcome of a lot of frames especially spins, in specific the artistic Biellmann spin, on which they all failed. This motivated us to further look into datasets, dataset creation and suitable neural network architectures for labeling figure ice skating videos, having in mind a good performing architecture, which would be able to run on mobile phones.

In this regard, we elaborated the creation of a figure ice skating dataset with the help of the XSens motion capturing data in a real figure ice skating arena environment in [chapter 3](#). In detail, we evaluated the creation of a dataset from these motion capturing data with the help of Blender and Makehuman in [subsection 3.1.1](#). We created an end-to-end fully convolutional architecture consisting of three modules for background extraction, body part and keypoint detection in [chapter 4](#). Since our work concentrates on pose estimation in single figure ice skating, the background extraction module is an indispensability. Multiple experiments with the network architectures, learning optimizers, and loss functions resulted in decent results, which can be applied in figure ice-skating and run on usual hardware, which we demonstrate in [chapter 5](#). At the end, we elaborate on several future thoughts, where these studies can continue to in [chapter 6](#).

## Chapter 2

# Figure Skating Pose Detection

### 2.1 Complexity of Figures

Figure ice skating includes very special movement sequences that stand out from other sports. Thanks to the surface of the ice, skaters perform gliding movements. Furthermore, their programs include highly artistic movements with explosive take-offs, very high rotation speeds, and flexible positions. Current pose estimators such as *OpenPose*, *VideoPose3d* or *wrncn.ai* all fail to correctly predict keypoints for spins with their high rotation speed and difficult flexible positions. In this section, we try to explain why especially figure ice skating means a challenge in human pose estimation.

In single figure ice skating, there are three main element types in a competitive program, which receive technical scores: jumps, steps, and spins. There are seven different listed jumps, which only differ in their take-off phase. Three of these are jumped just from one edge, the Axel, Loop, and Salchow. The other ones additionally use the skate toe as a catapult. In fact, they can be distinguished by the edge that is last skated on the ice before the skater takes off. This is one of the reasons, why many skaters have problems with the Lutz and Flip jumps. For the jury it is often hard to tell as well, whether the jump should get an edge deduction. All the jumps can include a different amount of rotation in the air, whereas four rotations were the maximum a skater could perform until today. All these jumps can be combined in various manners, include features such as lifted arms or difficult steps before or after the element to increase the level of difficulty, resulting in higher scores.

For spins, there are four main positions: upright, sit, camel and layback. These

positions as well can be combined with various features, as for example jumps or difficult elastic positions such as the famous Biellmann position.

There are plenty of different step sequence elements including turns on the ice and steps. These as well can be combined with multiple additional features resulting in higher scores.

The above-named elements only explain the absolute basics in figure ice skating. In practice scoring and the creation of ice skating programs is much more difficult. Nevertheless, this illustrates nicely, that however for the not professionalized audience many elements may look the same, there are plenty of different metrics and components. Moreover, each skater has their own style and performs these elements slightly different. This is what makes it so hard for machine-learning algorithms to correctly predict the elements. Which is why it is important that the basis, the key-point recognition module, has to predict the poses correctly. Because otherwise the action recognition module has no chance to make correct estimations [21, 57].

## 2.2 Distinct Rating System

First reported figure ice skating competitions with a registered scoring system took place in Vienna in 1881. The International Skating Union (ISU) regulates figure ice skating competitions since 1892 and is responsible for the construction and further development of its judging system. The old, still very well known judging system 6.0 was officially used until the world championships in 2004, and is still used very rarely at tiny competitions or fun competitions, due to no special technical equipment requirements. This system allows grades from 0-6 with 6 standing for best outstanding skating. Further refinements could be rated via decimal numbers. A program receives grades *A* and *B*, with the A-Grade rating technical skills and the B-Grade judging performance gratitude and expression. Both grades added resulted in the placement of the skater, where placement proposals of the judges were combined via the majority principle, resulting in the final placement.

Since the more and more rising complains [29], a new system was developed to increase fairness, today referenced as ISU Judging System. This new system was



adjusted several times since it's first introduction in 2004, and only recently in 2019 got updated fundamentally in it's GOE scores. It assigns a base value to every jump, step sequence, or spin type in the still existing technical *A-Grade* part. Furthermore, several features rise the GOE for jumps, as for example lifted arms or the base value as for spins. The step sequences as well include special regulations to achieve certain levels and gain a higher base score. These base scores can become higher or get deductions via the GOE part. For example, a fallen jump gets its jump value with a GOE of -5.

The *B-Grade* judges the skating skills, program transitions, performance or execution, choreography and interpretation. Also costume choice and interpretation of music play part in this grade. Great about the new system is, that the programs are recorded via video, and the technical specialists can review, slow down and zoom into the element. The GOEs then are given by separate judges.

Another benefit of this new system is the comparability between competitions and the transparent display of how a certain final score was achieved. Skaters can even collect points from several competitions to get special sponsorships as for example the Kader.

One drawback however is the complexity of the new judging system. Moreover, it requires special technical equipment calculating all the points and for reviewing the programs. Additionally today, all programs have very specific rules, which elements are allowed or have to be performed. Which is why some people complain about the resemblance of the different programs and the missing own interpretation freedom.

However, the traceability of scores rose, there is still a very high degree of subjective input in the results, about which many people complain. This starts from the first stage of the technical specialist rating a jump with certain deductions or not, and then of course is passed to the judges, who pass in their GOE estimations for the elements. The *B-Grade* still remains very subjective and unfairness is a topic at almost every competition [21, 29, 57].



## Chapter 3

# Dataset

### 3.1 Figure Skating Dataset

The correct dataset with the according labels is what decides whether a neural network architecture will be able to successfully learn keypoints from image data or video sequence data. As of today, there does not exist a publicly available dataset which labels keypoints to ice skating performances or elements. Famous existing ones such as FIS-V or the MIT datasets only include the total technical and performance scores of the complete performances, which are not applicable here as explained in [chapter 2](#).

To create a reasonable dataset for figure ice skating there are various possibilities. Most straightforward would be to make use of the huge amount of videos published everyday on online platforms such as *YouTube* and label the videos by hand. This however would cost a huge amount of time and includes outliers coming from human errors. Another possibility would be to work with motion capture.

#### 3.1.1 Motion capturing techniques

There are three main methods for recording motion capturing data.

Markerless capture is a method where videos are recorded via a single or multiple depth cameras. This comes with the advantage that the athletes are not distracted or feel uncomfortable by any markers [[18](#), [26](#), [40](#)].

When working with markers there are two sensor types: optical or inertial. Optical markers are reflective markers, which are attached to characteristic parts of the

body. These reflections are tracked via multiple cameras to make sure the motion movements are taken especially when a person is moving, so the markers are not concealed [59].

Inertial motion capture uses IMU sensors that are attached to body parts [33, 65]. 3D positions then are calculated via multiple sensor metrics. The XSens system for example includes several trackers that contain magnetometers, gyroscopes, and accelerometers. Via their MVN Animate and Anlaze systems, the tracked data is post-processed on a biomechanical model and then can be used in game engines such as *Unity* or *Unreal*, or in 3D animation software such as *Blender* or *3DSMax* [1].

In an environment such as the ice rink, motion capture has to deal with several difficulties. For one, the lighting is often not smooth and there are several different light sources. Moreover, it is very difficult to get the whole ice rink for a recording, because most of the time the ice rink is fully booked with figure ice skating, ice hockey, public skating or short track speed skating. Further, many ice rinks are governed by the local community [12], or are highly expensive to rent. This makes markerless and optical recordings very challenging. On the other hand, inertial recordings as by the XSens technology seem very promising. Even when there are multiple skaters on the ice, recordings can be tracked in usual practice time slots.

### 3.1.2 XSens: Inertial motion capturing recordings on the ice rink

In our research study, we tested recordings on the ice rink with the MVN Link product from XSens. This product includes 17 wired IMU motion trackers which can be either attached into a suit or onto straps. The sensors are connected via cables to a battery with a lifetime of 9.5 h. These trackers are then connected via a router to their MVN Animate software. The wireless range of the trackers is 50 to 150 meters, however, the trackers are able to buffer the recordings and transmit these later when there is a connection to the hub. Their MVN Animate software helps with calibration and shows the recording results as soon as the trackers are close enough for transmission. Furthermore, it processes the data and performs adjustments in a postprocessing step [31].

### Our experiences with MVN Link from XSens

The overall setup was very time-consuming. To correctly attach all the straps and align the cables took us a minimum of 20 minutes. Here we tried out the suit and the straps with equal preparation times. Then the calibration on the ice with the MVN Analyze software was very time-consuming again and took about 20 minutes. The calibration process had to be repeated several times when the calibration failed. These problems probably came from the different gliding movements on the ice. So the skaters had to mimic usual floor movements for the calibration to work correctly. Since the recordings are very time-consuming we could not work with young professional competitive skaters, because the setup was too drawn-out. We then took recordings from a senior competitive skater. The inertial method was very beneficial here because other skaters on the ice did not intervene in the recordings. Additionally, however, sometimes the connection was lost to the hub, when the skater came back the recordings were transmitted correctly. The post-processing from their software did work really good as well. What was disruptive, however, were the sensors and battery, which the skater had to carry. This made the movements feel constrained. Indeed, in figure ice skating falls are very common. A fall on the battery or one of the sensors would have been harmful, which again influenced the movement of the skaters. In comparison, there are other products on the market, that promise a faster setup e.g. through a suit in which the sensors are integrated without cables [33]. These products would very likely better fit for figure ice skating motion captures.

### Dataset Creation with Blender and MakeHuman

We processed the recorded data from the XSens trackers in *MVN Animate* and then exported a short sequence as BVH file to test possible dataset creation procedures. Further, we used the open-source *MakeHuman* [28] program to create a figure ice skating avatar. Here we used the figure ice skating dress and ice skates, which are freely available from the MakeHuman community [58]. With the help of the MakeHuman plugin in Blender 2.7 [4] we then imported the created avatar from MakeHuman and retargeted the BVH motion capture file onto the rig. We then set up a default scene with lighting and a moving camera. To obtain the keypoints, we wrote a Python script in Blender to calculate the joint locations in relation to the camera

view and exported the resulting keypoints into NumPy files.

However, the above-described process seemed to be smooth to conduct, we did face a couple of challenges. For one, artistic elastic movements yielded in errors on the armature, since the joints were restricted to certain regions of movement, which seemed to work for usual daily activities but not figure ice skating ones. Another one was that with the moving camera the keypoints were not calculated correctly and drawn with a small offset. Recent research studies suggest to export the animation as BVH files and later calculate the joint positions with a program such as Matlab [7, 37, 46]. So this could improve the calculations of joint positions.

### **Our conclusions on creating a synthetic dataset in figure ice skating**

We are convinced that the above-described process to create a synthetic dataset for figure ice skating is an indispensability when it comes to figure ice skating, because of the following reasons:

First, with inertial motion tracking is very accurate especially in an environment such as an ice rink when recording can be easily be done during practice sessions.

Second, much fewer recordings are necessary thanks to the large arbitrary degrees of variation which is possible with an animation software such as blender.

Third, the diversity of data is exceptionally vast.

From one small motion capture file, multiple different avatars can be retargeted, female and male, age variations, clothes and race variances. Further, multiple different light sources and camera views can be applied and the background randomly selected.

Fourth, calculated labels by the associate animation software or post-processing program are just more exact than human labeled data.

All these points confirm the legitimacy of synthetic datasets in figure ice skating. Which is why we researched on already existing synthetic datasets since in the scope of this thesis creating our own dataset was not possible due to the huge time efforts. The synthetic dataset 3DPeople as described in the next section corresponds to our expectations of an appropriate dataset.

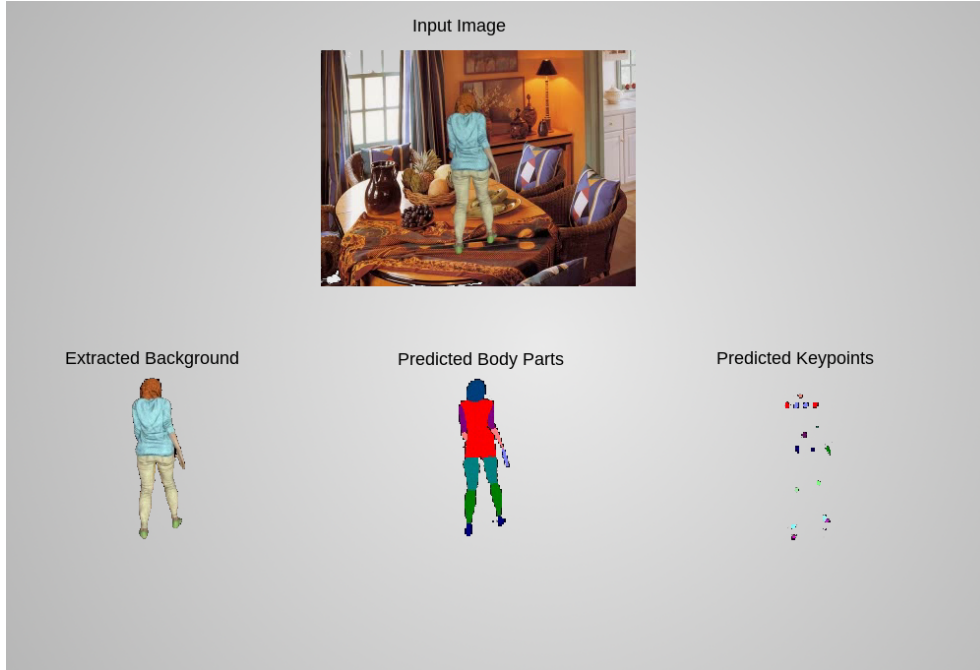


FIGURE 3.1: Learned labels from a image sequence of the 3DPeople dataset: Woman stiff walk

## 3.2 Synthetic Dataset: 3DPeople

The dataset 3DPeople was created via recorded motion capture files. They took 70 realistic action sequences from Mixamo [30]. The sequences contain on average 110 frames and range from usual activities with little motions such as driving or drinking until break dance moves or backflips. These actions they then retarget onto 80 armatures which are created with MakeHuman [28] or Adobe Fuse [27]. There are 40 female and 40 male characters with plenty of variation in body shapes, skin tones, outfits and hair. Furthermore, they record the actions with a projective camera and 800 nm focal length from four different viewpoints which are orthogonally aligned with the ground. The distance to the subjects vary arbitrary as do light sources and static background images. In sum the dataset includes 22,400 clips with the rendered video sequences as 640x480 pixel image frames, the according depth maps, optical flow and semantic information such as body parts and cloth labels [37].

We found this dataset highly sophisticated due to the wide variance and diversity of the data. Especially in terms of clothes it stands out from other famous datasets such as Human3.6M [47]. They use a variety of wide and tight clothes. For example do they include dresses and shorts. There variance is greater compared to their freely

available combats [19, 47]. In Figure 3.1 we demonstrate the learned labels of our modules from a random image of the 3DPeople dataset.

### 3.3 Data Processing

The 3DPeople dataset can be recreated through their project homepage and is allowed for use in research environments. Each data package consists of five batches for women and men. There are five data packages available for download. We created a *data\_admin python class*, which takes care of downloading the data, processing and storing the data in memory agnostic and efficient access structured compressed numpy files, and delete the initial downloaded data. We included several processing steps: In sum we created four compressed numpy archives. Every archive file included an array with all frames of one movement sequence to allow faster reading process for our neuronal network training later. The four archives consist of the usual RGB sequence frames, one archive without background, one for the body part labels, and one for the joint keypoints. The numpy archive without background only shows the actors in RGB colors. Therefore, we used the clothes labels, and replaced all colored pixels with black pixels when the pixels were not inside the mask. Initially we did this to test, whether our network ideas would converge with easier data. Later, when we trained our background-extractor module for getting an end-to-end architecture, this data served as labels.

Furthermore, we cleaned up the body masks and mapped the resulting three dimensional pixels to one-dimensional class values Figure ?? . The borders of the body-parts often contained a mixture of RGB values, which were of no use to our network.



```
— Mapping to classes —
body_part_classes = {
    BodyParts.bg.name: 0,
    BodyParts.Head.name: 1,
    BodyParts.RUpArm.name: 2,
    BodyParts.RForeArm.name: 3,
    BodyParts.RHand.name: 4,
    BodyParts.LUpArm.name: 2,
    BodyParts.LForeArm.name: 3,
    BodyParts.LHand.name: 4,
    BodyParts.torso.name: 5,
    BodyParts.RThigh.name: 6,
    BodyParts.RLowLeg.name: 7,
    BodyParts.RFoot.name: 8,
    BodyParts.LThigh.name: 6,
    BodyParts.LLowLeg.name: 7,
    BodyParts.LFoot.name: 8
}
```

```
———— Mapping to RGB values ————
segmentation_class_colors = {
    BodyParts.bg.name: [153, 153, 153],
    BodyParts.Head.name: [128, 64, 0],
    BodyParts.RUpArm.name: [128, 0, 128],
    BodyParts.RForeArm.name: [128, 128, 255],
    BodyParts.RHand.name: [255, 128, 128],
    BodyParts.LUpArm.name: [0, 0, 255],
    BodyParts.LForeArm.name: [128, 128, 0],
    BodyParts.LHand.name: [0, 128, 0],
    BodyParts.torso.name: [128, 0, 0],
    BodyParts.RThigh.name: [128, 255, 128],
    BodyParts.RLowLeg.name: [255, 255, 128],
    BodyParts.RFoot.name: [255, 0, 255],
    BodyParts.LThigh.name: [0, 0, 128],
    BodyParts.LLowLeg.name: [0, 128, 128],
    BodyParts.LFoot.name: [255, 128, 0]
}
```



## Chapter 4

# Method

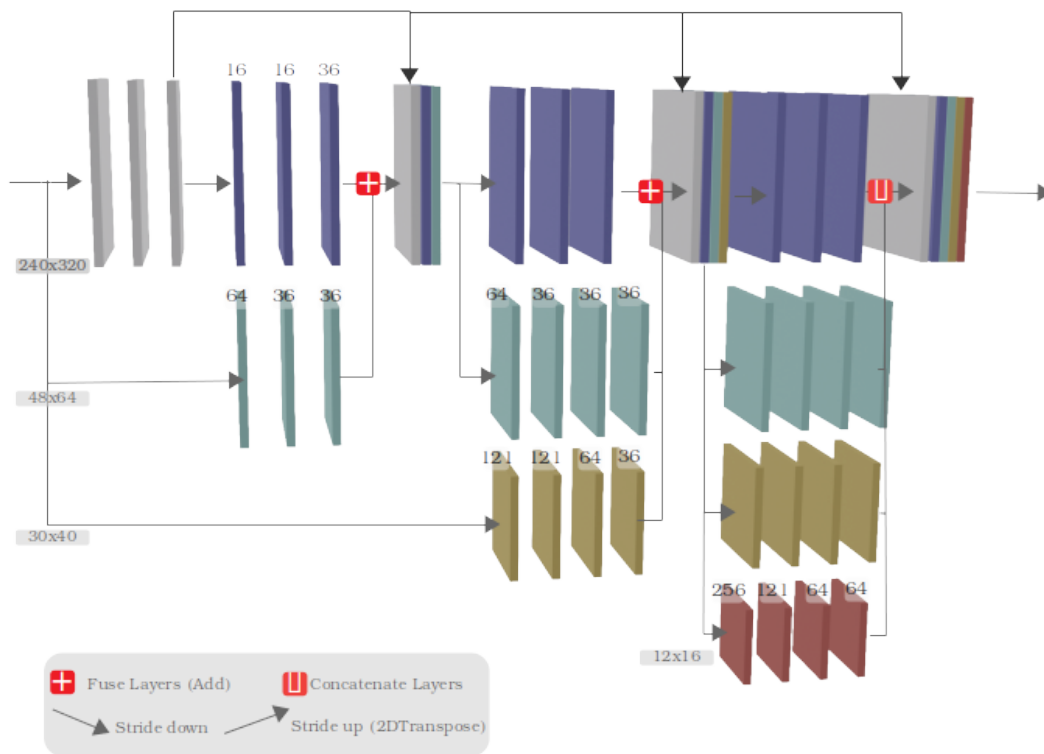


FIGURE 4.1: High-to-low representations network architecture

For our end-to-end keypoint recognition architecture we have created three modules to extract the background, find the body parts in the image and detect the human joints or keypoints. However, to extract the background was not important for other keypoint recognition architectures such as OpenPose [5] or VideoPose3D [36], it is important in our architecture, since we wanted this recognition architecture to be able to be used during practice, when there are multiple skaters on the ice, but only track the focused skater. With the body part detection module we altered the well established approach from OpenPose not to recognize vector fields, which the

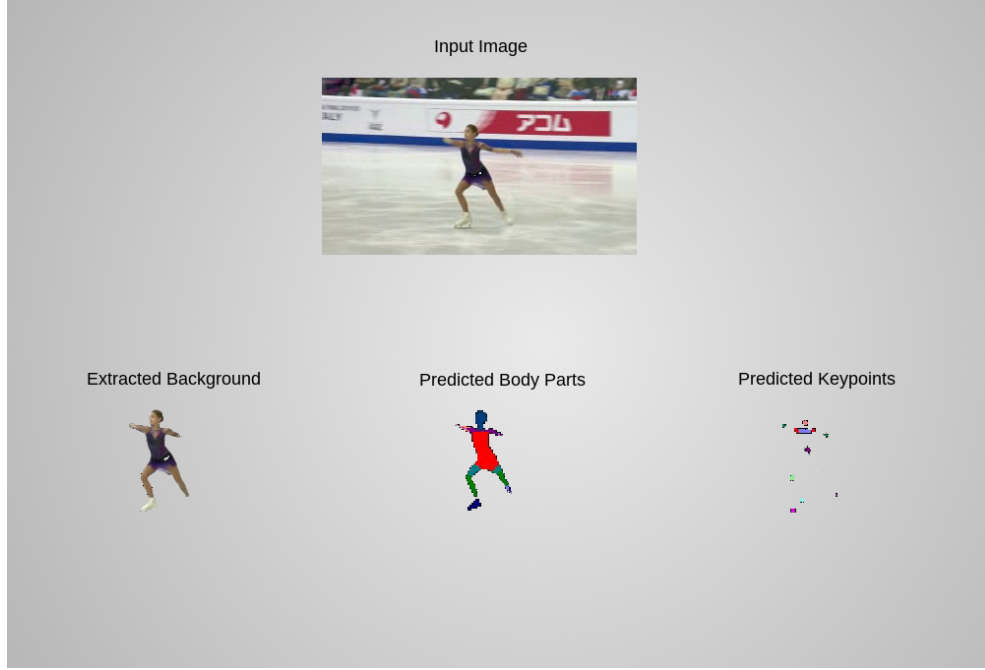


FIGURE 4.2: Learned labels by the three modules: extracted background, human part detection and keypoint detection *skater: Alena Kostornaia, 2020 European champion*[56]

joints connect, but the visible body parts. We assume this method to work seamlessly, and estimate that this approach was not chosen before due to the missing accurate labels for body part detection. For the keypoint recognition module, we calculate the gaussian with a radius of three pixel and a standard deviation of three. In Figure 4.2 we demonstrate an example frame labeled by our three modules showing Alena Kostornaia, the 2020 European champion during her program.

All in all we have build a fully convolutional architecture with three networks, that all are based on high-to-low representation learning. Our architecture consists of one input block  $\mathcal{N}_I$  and three subsequent blocks  $\mathcal{N}_L$ ,  $\mathcal{N}_M$ ,  $\mathcal{N}_S$  and  $\mathcal{N}_{XS}$ . These subsequent blocks combine feature maps with lower coarser representations with the original sized input image feature maps and thus learn the features of the different levels equal to the HRNet strategy [22, 61].

However, different from the HRNetV1 and HRNetV2 we do not use pooling to decrease or increase the size of the feature maps. We decrease the feature maps with usual convolutions and accoring strides  $s$  and kernel sizes  $k$ , with  $s = k$ . To increase the feature maps we use transposed convolutions with again  $s = k$  according to the strided down convolutions. This allows the network to learn additional weights

for the upward and downward convolutions and improve these level exchange processes.

Furthermore, we fuse the layer blocks in the first and second stage to combine the mentioned feature levels. In the third stage however, we concatenate all feature levels to fully exploit the multi-resolution convolutions as argued in HRNetV2 [22].

As visualized in 4.1 we adjusted the amount of feature maps for the different blocks. Moreover, in the first stage we use only three convolutional layers for one block in the other stages we use four layers for the lower levels and only in  $\mathcal{N}_L$  we use only three convolutional blocks throughout the network.

Another adjustment is, that we use the input image as initial input for all our block levels but the  $\mathcal{N}_{XS}$  block, which uses the fused layers of all the other levels as input. To every stage we add the input block  $\mathcal{N}_I$ .

This network architecture resulted after several experiments and investigations of the estimated feature maps of the different blocks and stages. Every block is completed with batch normalization and a *selu* activation functions. The output of the network is predicted by a linear softmax activation function. For the background-extraction and keypoint detection network we use mean-squared-error as loss functions and in the human part detection network we use a custom loss function ?? to optimize the network weights. In sum our network comprises 3,008,562 parameters of which 3,003,930 can be learned. The amount of all layers for one network is 156.

## 4.1 Training Performance (human parts)

We trained the human parts module with the Adam optimizer for 5556 episodes, a batch size of 3 and 64 steps per epoch. One training epoch took on average 85.43 seconds and took about 5.5 days. For optimization we have build a custom loss function as explained in ?? to better deal with the class invariance of the occurring pixel labels. The Figure 4.3 shows, that the accuracy of our network Figure 4.3 rises very steep until the 500th episode and then flattens more and more until the last

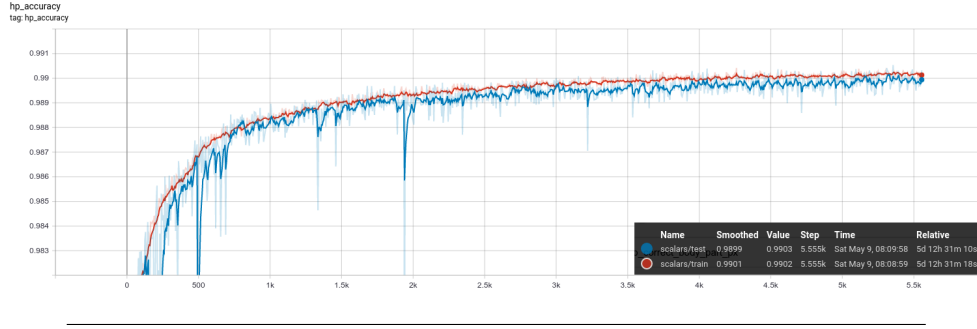


FIGURE 4.3: Learned labels by the three modules: extracted background, human part detection and keypoint detection *skater: Alena Kostornaia, 2020 European champion*[56]

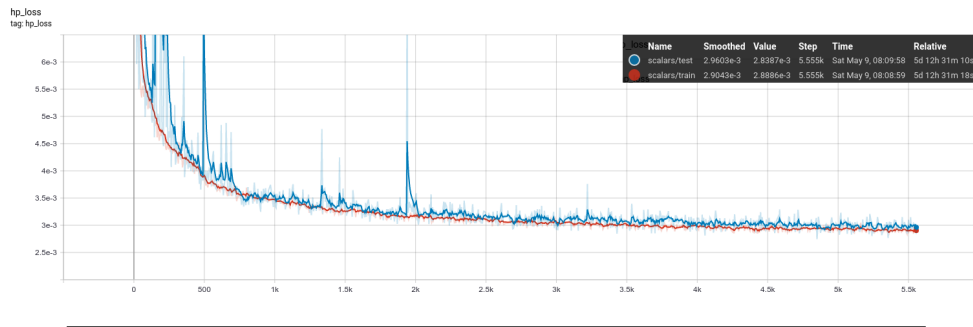


FIGURE 4.4: Learned labels by the three modules: extracted background, human part detection and keypoint detection *skater: Alena Kostornaia, 2020 European champion*[56]

episode, where the network reaches an excellent accuracy level of 0.99. Furthermore, we divided our data in a distinct 90 percent train and 10 percent test dataset. The figure shows equal trends for both datasets, which means the network did not overfit on the data.

The loss function in Figure 4.4 shows equal opposite trends to the accuracy graph. It steeply decreases until the 500th episode and then starts to flatten. Again train and test dataset do not cross each other but show similar courses.

## 4.2 Inference Runtime Analysis

The time to predict one frame of size 640x480 pixel takes about 0.3 seconds run on a Quad-Core Intel i7 CPU with 2.20 GHz, a simple laptop cpu. Predictions and training can run on simple hardware as the above mentioned cpu. The training speed will increase if the minimum version of Cuda 3.5 is supported by the system, since then tensorflow 2 is able to run on the gpu instead of the cpu. Due to the age of the named laptop cuda 3.0 was the highest to be supported. Since recent

developments targeting AI chips in the mobile world by the common companies Apple, Samsung or Huawei, we are very confident that inference of our network does work as well on common sold mobile phones today [32]. This sets apart our architecture from OpenPose, which we could not use for inference on the mentioned laptop.

### 4.3 Implementation Details

We build our Network upon the high-level API TensorFlow 2 which is based on the Keras API [52]. Our training run on the AI server *J.A.R.V.I.S.* provided by the Stuttgart Media University. The server contains four Nvidia Titan Xp GPUs with 12 GB RAM and a i7 8-core CPU with 3.2 GHz. We trained each experiment on a separate GPU. The training was conducted in docker containers using the TensorFlow *latest-devel-gpu* [51] docker build. The latest TensorFlow docker container did not support Python 3 at the time of this research, but only Python in version 2, which is why we had to use the before mentioned descendant.





## Chapter 5

# Experiments

We conducted several experiments on our human parts and keypoint detection module. We applied the resulting network architecture from the human parts module later to the background extraction module. In sum we investigated eight network architecture variants differentiating in commonly discussed parameters. For the keypoint detection module we conducted tests with and without Dense layers. On the human parts detection module we tested the three state-of-the-art optimizers Adam, Nadam, and SGD and experimented with little modifications to the SGD optimizer. To overcome class invariance, we tried out three different loss functions under which one we have come up with ourselves. In the following section we will present our experimental setup, results and constructive thoughts behind the studies.

## 5.1 Ablation Study

### 5.1.1 Body Parts Detection Module

In 5.1 we demonstrate our network architectures, which range from 88 until 177 layers and are all fully convolutional networks. The HRNet (*traditional*) 5.1.1 we slightly deviate the HRNetV2 presented in [22] by replacing the pooling layers with strided-down and transposed convolutional layers. The amount of levels and sizes of the feature maps correspond to 4.1. As in HRNetV2 we use 4 stages with a filter size of 64 for each stage. We add one level per stage starting with just the highest level  $\mathcal{N}_L$  and concatenate the levels from stage 2 ongoing as demonstrated in HRNetV2.

For the HRNet (*filters*) 5.1.2, we adjust the filters in a way, so that higher levels use less filters than lower levels. Additionally, we decrease the filters from the convolutional layers in the level blocks, starting from the highest filter amount reducing until 36. All levels are concatenated with a filter size of 36.

TABLE 5.1: Ablation Human Parts Module: Network Architecture Comparison

	Name	Parameter Amount	Trainable Parameters	Layers	Training Time/Epoch
5.1.1	HRNet - <i>traditional</i>	5,595,221	5,589,237	171	84.76s
5.1.2	HRNet - <i>adjusted filter</i>	4,936,997	4,933,029	171	66.23s
5.1.3	HRNet - <i>3 stages</i>	848,409	846,441	100	82.33s
5.1.4	HRNet - <i>stride-down-up</i>	4,953,269	4,949,157	177	63.21s
5.1.5	HRNet - <i>stride-down-up-input</i>	4,185,605	4,181,493	177	80.57s
5.1.6	HRNet - <i>add-input</i>	4,185,605	4,181,493	177	80.57s
5.1.7	HRNet - <i>add-depthwise-conv</i>	3,182,342	3,177,654	156	83.10s
5.1.8	UNet	656,389	654,261	88	85.37s
5.1.9	HRNet - <i>v3</i>	3,008,562	3,003,930	156	85.43s

Subsequent architectures all make use of the adjusted filter amount.

For the HRNet (3 stages) 5.1.3, we use only the three first stages from 5.1.2 and omit  $\mathcal{N}_{XS}$ . In HRNet (stide-down-up) 5.1.4, we stride down the Input from 240x320x3 to 120x160x36 and use this layer as Input layer and highest Level  $\mathcal{N}_L$ . Lower layers scale relatively to  $\mathcal{N}_L$ . The HRNet stride-down-up-input 5.1.5 uses the intially strided down input layer as input for every stage instead of the concatenated results for lower levels.

As presented in the mobilenet paper [48] in 5.1.7 we experiment with depth-wise convolution and replace the concatenation layers after each stage with add layers.

In the UNet 5.1.8 we use all levels and combine them via concatenation according to the traditional UNet [43].

Finally, we present our resulting high-to-low resolution network HRNet (v3) 5.1.9, where we fuse the first stages and only concatenate the last stage. Furthermore, we conducted some adjustments to the layer amount in the levels and stages as presented in ??.

The HRNet stride-down-up 5.1.4 seems to train the fastest, when looking at 5.2 the 4.705kth step, it is only at three days and 13h closely followed by the traditional HRNet with the adjusted filters 5.1.7 which is at 3 days and 13h. All other trainings took more than four days at that time. However, one has to keep in mind that these both trainings where conducted at the same dates, and the other dates differ. So the server

could have had other workload, nevertheless, our trainings were the only ones running on the server most of the time. This occasion as well is reflected in the training time of one epoch. There we measured the third epoch to omit starting warm up phases. There as well both the HRNet *stride-down-up* and HRNet *adjusted-filter* only took about 63, 66 seconds, where all the others took more then 80 seconds. However, we would have expected the U-Net or HRNet 3 *stages* to be the fastest, since they have the smallest amount of layers and trainable parameters. Further, the HRNet *stride-down-up-input* contains less trainable parameters then *stride-down-up*, so we would have expected a faster training process here. This verifies that the measurements are dependent from various circumstances.

### Comparison of network architectures

The U-Net 5.1.8 has the smallest amount of layers with 88 and 654,261 trainable parameters. The HRNet *stride-down-up* 5.1.4 composes most trainable parameters with 4,949,157 and 177 layers, since the input layer is first strided down and at the end transposed up again. On the other hand due to the reduces feature map sizes this reduces the computation effort as well. All comparison figures show very similar curves. Since we could only run our experiments one complete training each, the results must be viewed circumspectly. All figures ?? show very steep curves until the 500th episode and start to flatten then.

When looking at 5.4 and 5.5 this steep initial increase is visually reflected. When after the first episode the circumferences of the body shapes are predicted vaguely, after the 20th episode the networks have already learned to predict the locations of body parts relatively close. Of course here has to be regarded, that the different predictions were made on different poses, which might differ in their complexity. Nevertheless, the UNet 5.1.8 and the HRNetV3 4.3 seem to accomplish superior performance. After the first episode, the body shape is already estimated precisely close to the input image. HRNetV3 even shows correct class estimations for different body parts such as torso, head, arms and legs already. The 20th episode then the labels seem to be estimated very close to the true labels.

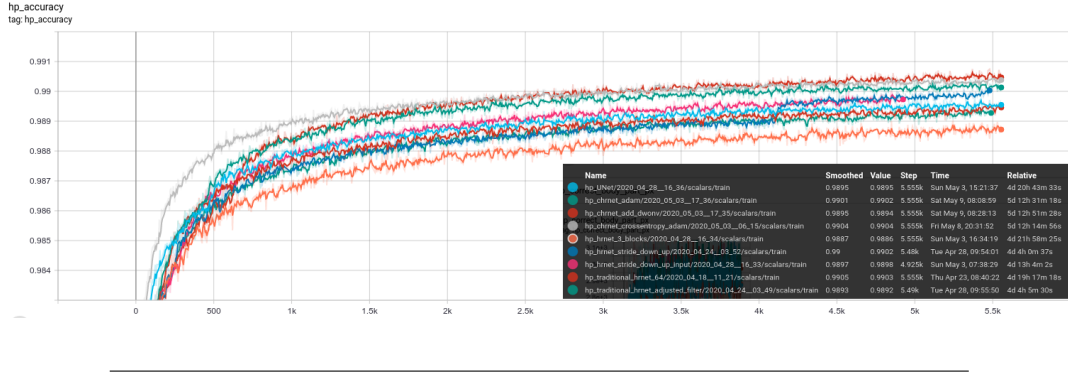


FIGURE 5.1: Ablation Human Parts Module: Accuracy Comparison

The accuracy graph shows that the HRNet *traditional* and HRNetV3 get the best results from epoch 500 onwards. At step 55.55k they reach 99 percent. However, the HRNet *stride-down-up* has a lower curve until the 4.3kth epoch, it then makes a jump in accuracy and at the end reaches 99 percent as well. Interestingly the U-Net with the by far fewest params and layers does receive very good results as well making almost 99 percent in accuracy at the end. The HRNet with only three stages shows the lowest curve and reaches only 98.87 percent points on accuracy at the end.

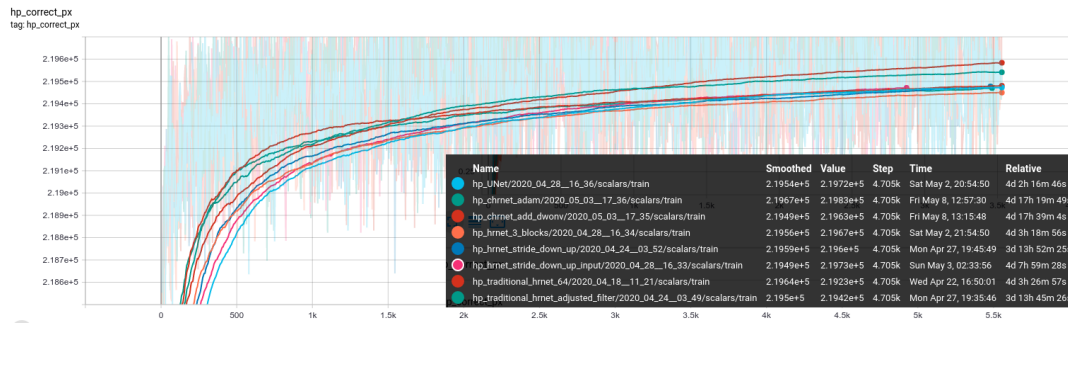


FIGURE 5.2: Ablation Human Parts Module: Correct Pixel

The correct pixel graph 5.2 measures how many pixels of the 240x320 image where labeled correctly in one batch. The maximum which could be reached here is  $240 \times 320 \times 3 = 230\,400$ . Since the single epochs vary a lot it makes more sense to look at the smoothed results. The curves again are very close to each other, with the best results coming from the HRNetV3 with umprint219670 and the HRNet *traditional* with 219 640. The lowest curve again shows the HRNet 3 stages.

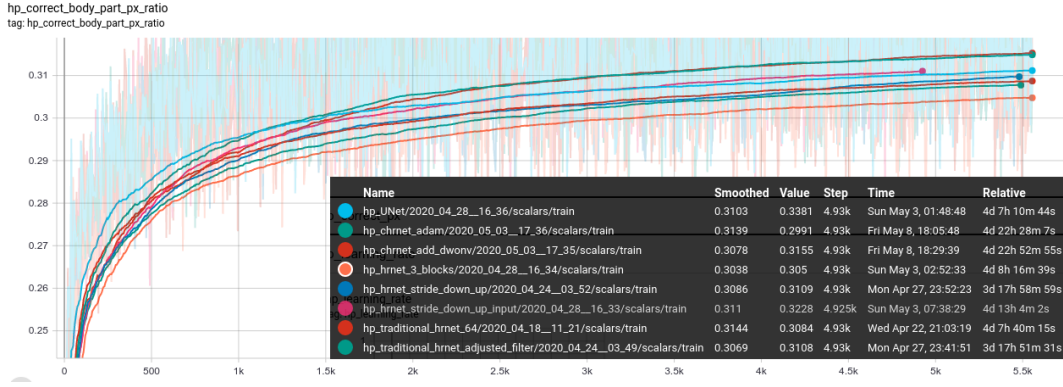


FIGURE 5.3: Ablation Human Parts Module: Correct Pixel Ratio

For 5.3 we summed up the amount of body part pixels and divided by the amount of correctly predicted pixels for one training batch. This figure as well displays high varieties for the different epochs, which is why it is important to take the smoothed values into account. We receive similar courses as already inspected in 5.2. The HRNet *traditional* and HRNetV3 take the lead with the *traditional* being slightly above the HRNetV3 with 0.05 percent points. With 31.44 percent the HRNet *traditional* shows best results, whereas HRNet *3 blocks* performs worst with 30.38 percent at step 4.93k.



FIGURE 5.4: Predicted images of network architectures after first episode

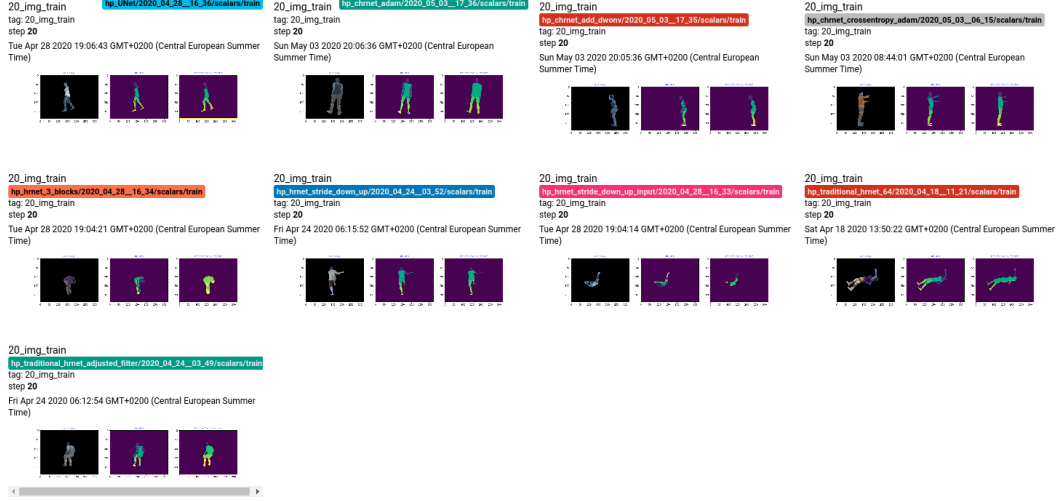


FIGURE 5.5: Predicted images of network architectures after 20th episode

## Summary

In summary our experiments show that our constructed HRNetV3 performs best, and the HRNet with only three stages performs worst. Interesting here would be different variations in the level of feature map sizes. For example what would happen if the level  $\mathcal{N}_{XS}$  was maintained as smallest level and the level  $\mathcal{N}_M$  was strided down slightly more. Insightful as well it the performance of the UNet, which has less than half of trainable parameters and layers compared to the HRNet *traditional* or HRNetV3, but does not perform much worse.

Additionally, further tweaks and studies in these network architectures applied to our different modules would be greatly enlightening.

### 5.1.2 Joint Detection Module

TABLE 5.2: Ablation Keypoint Detection Module: Network Architecture Comparison

	Name	Parameter Amount	Trainable Parameters	Layers	Training Time/Epoch
5.2.1	KPS-Dense - <i>block_L</i>	221,748,579	218,735,769	51	68.75s
5.2.2	KPS-Dense	23,097,980	20,086,328	13	67.05s
5.2.3	KPS-FCN	4,119,529	1,109,991	41	63.78s

### Network Architectures

We created three variations of keypoint detection network architectures of which two?? utilize Dense layers to estimate the keypoint locations and KPS-FCN 5.2.3 implements the third stage of our build HRNetV3.

KPS-Dense 5.2.1 additionally to the dense stage utilizes the third stage of the HR-NetV3.

The dense stage first uses max pooling to reduce the feature map size from 240x230x9 to 120x160x1, 58x78x32 and then 28x38x64. The resulting pooling layer is flattened and followed by two dense layers, which are combined with AlphaDropout and batch normalization. The layers include 1024 and 512 units. The first dense layer is conneted to a softmax activation function, the second to a linear activation function. The model estimates 38 x,y coordinates for the keypoint locations. The networks loss function calculates the distance from the predicted keypoint locations to the true locations and optimizes the networks via mean-squarred-error.

For the KPS-FCN 5.2.3 only uses convolutional layers. The true labels calculate gaussians with a radius size of three for the locations of the keypoints. We combined the keypoint classes for equal body locations such has legs and arms, resulting in 11 joint classes. This network predicts 11 different labels for the classes. The network is optimized as well with mean-squarred-error.

All networks are trained with an Adam optimizer and a learning rate of 0.001 and run for 5556 epochs.

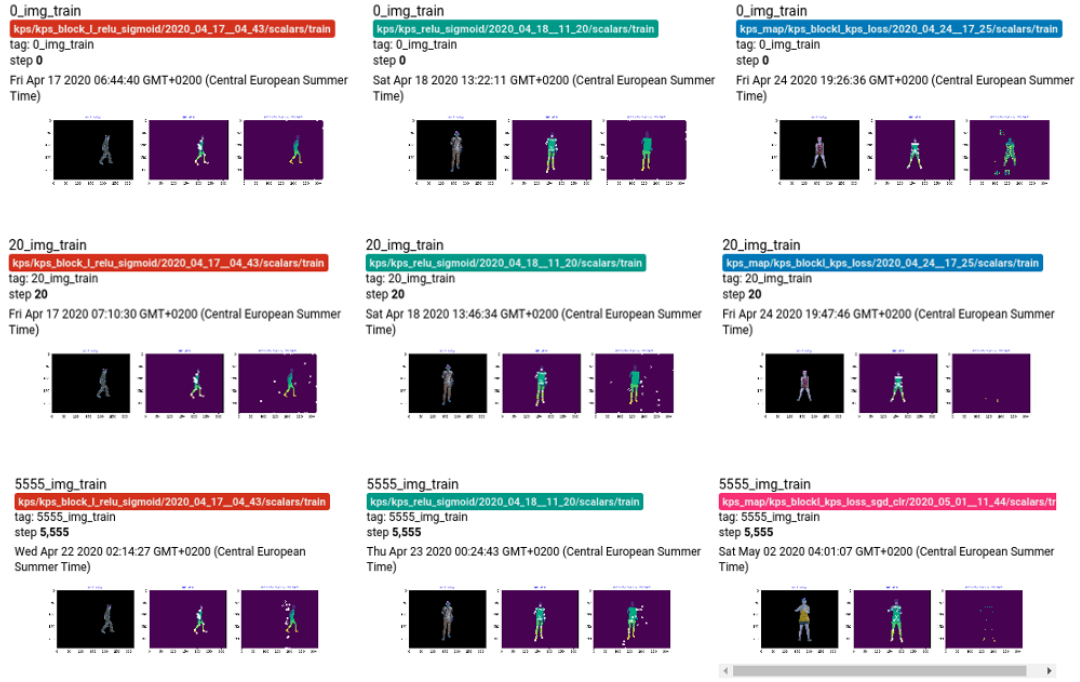


FIGURE 5.6: Predicted images of keypoint detection networks after first, 20th and last episode

Both figures 5.7, 5.8 show similar curves. Until the 500th episode they decrease steeply and then they start to flatten. KPS-Dense 5.2.2 has the fewest layers with 13, however KPS-FCN 5.2.3 contains only 1,109,991 trainable parameters, the dense networks train 20/ 218 times more parameters. The networks only differ slightly in their training epoch time and are all between 63 and 69 seconds.

The main difference though is visible in the predicted training images in 5.6. The keypoint detection modules seem not to learn the locations of the body parts, but that the probability of the location of a keypoint being at the center of the image is much more likely than outer locations. Very interesting about the KPS-FCN is that this network first learns the locations of the feet, and then slowly goes upward per epoch learning the other keypoint locations in a continuous way.



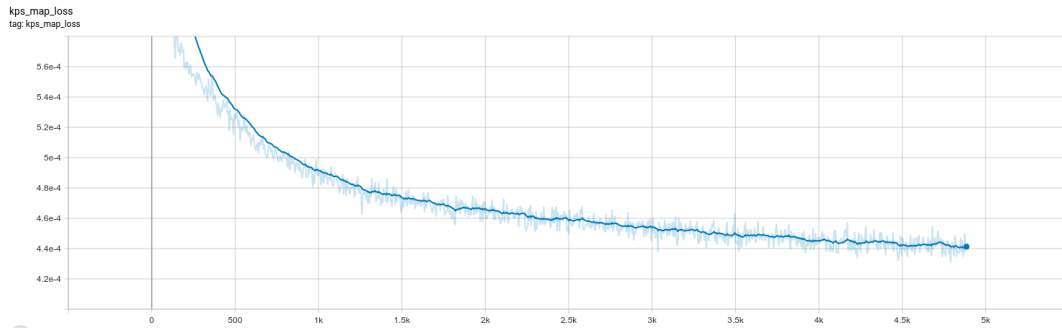


FIGURE 5.7: Predicted images of keypoint detection networks after first, 20th and last episode

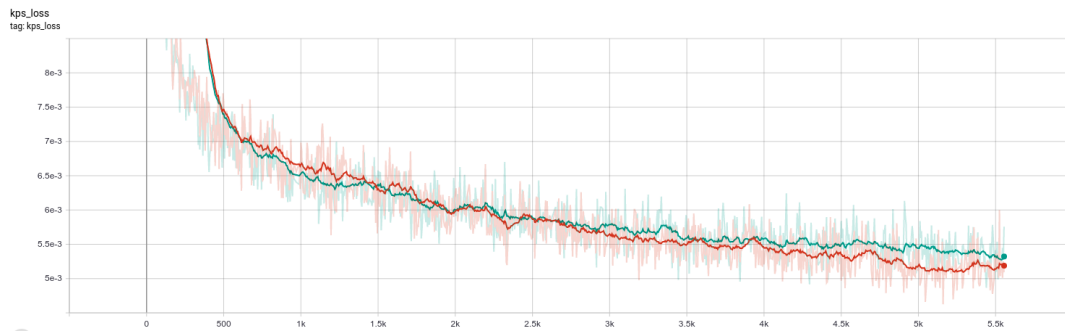


FIGURE 5.8: Predicted images of keypoint detection networks after first, 20th and last episode

## 5.2 Comparison of Optimizer Algorithms

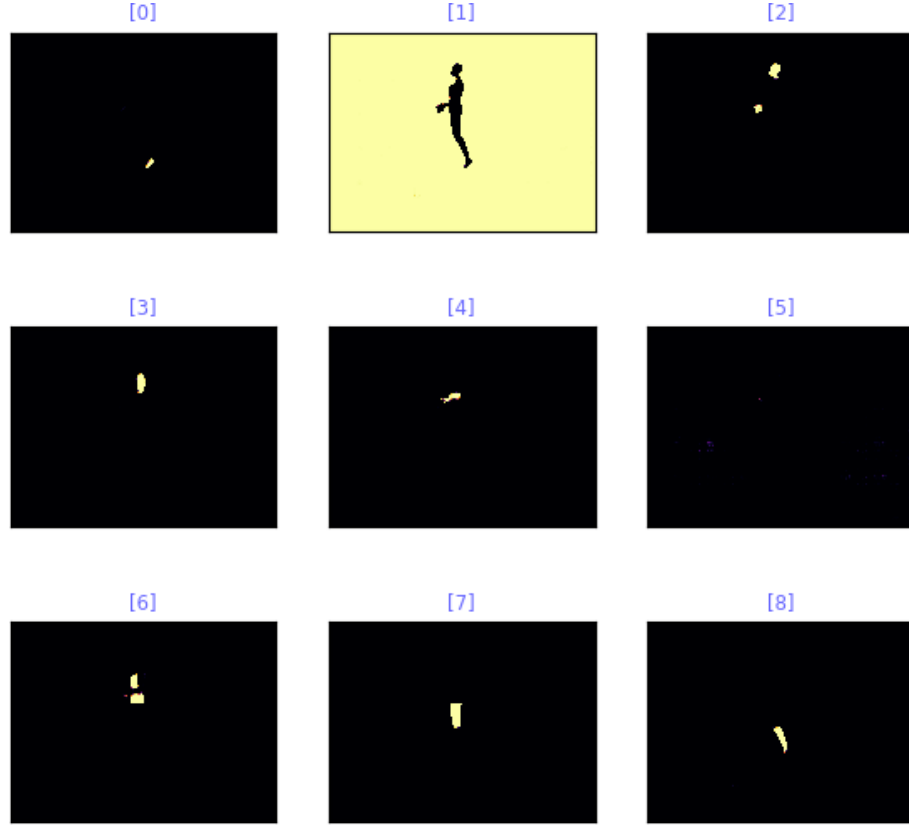


FIGURE 5.9: HRNetV3: Predicted 9 feature map classes of the output layer of the human part detection module

Optimizing the weights of a neuronal network is a crucial step in the training life cycle of deep learning. When our neural network has processed the input image and calculated several feature maps throughout the process, at the end it predicts 9 feature maps of body parts for example for head, arms, torso and legs for the human parts detection module 5.9. With the help of a loss function we then calculate the error for the predicted pixels in comparison to the truly labeled pixels. The optimizer updates the network parameters  $\theta \in \mathbb{R}^d$ , which result in learned filters predicting several feature maps at the different stages of the network. The updates are performed accordingly to the calculated error from the loss function  $\mathcal{J}(\theta)$  via the so called Backpropagation process, since the updates are passed backward through the network. This backward optimization process is performed by the calculations of the chosen optimizer. The goal of the optimizer is to minimize the error. There, it

makes use of gradient descent to update the network's weights, biases and activation functions, in opposite direction of the gradient. Figuratively speaking, a weight could be imagined as a hill. The updates then will follow the direction of the slope downhill until the valley is reached. Whereas the valley is equal to a local minimum [45].

There are three variants for gradient descent:

**Batch Gradient Descent (BGD)**, which calculates the gradients  $\theta$  for the entire training dataset. The problem here is, that most of the time this would not fit into the RAM. We for example had problems with data overflow when we trained with more than 12 images at a time, however we even reduced the image size to 320x240. Another drawback is, that gradients for similar examples must be recalculated before each update, leading in redundant computations.

**Stochastic Gradient Descent (SGD)** confronts this problem by performing updates for each training example input image  $x_i$  and mask label  $y_i$ . This optimization process is much faster. Moreover, the updates are of more variance when random training examples are chosen. A drawback however is, even if jumping around may result in finding another better local minimum, it may also lead to constantly overshooting the exact minimum. Against this problem, slowly decreasing the learning rate may help and lead to similar convergence as for BGD.

**Mini-Batch Gradient Descent** is the most common variant for gradient descent since it combines the aspects of BGD and SGD. The updates are conducted for every mini-batch of  $n$  training samples. This reduces the variance of parameter updates and leads to less jumping around, which all in all results in more stable convergence [45].

In the following section we will present an overview on optimizers targeting the optimizers we experimented on, which are SGD, Adam and Nadam. We conducted our training with Mini-Batch Gradient Descent with a batch size of three. In the upcoming section we will present some mathematical backgrounds of optimizer algorithms and explain further aspects of SGD in more detail.

## Overview of our used optimizers

**Stochastic Gradient Descent (SGD)** is one of the first optimizers and still commonly in use. Already in 1951 it was publicly reported by Robins and Sutton et Al [42]. Now given a neural networks parameters  $\theta$ , such as weights, biases and activation functions, here via an input image  $x$  and according labels  $y$  the Backpropagation process is defined under the gradient  $\nabla$  from the calculated loss function  $\mathcal{J}$ . The adaption of the parameters then is performed stepwise by the learning parameter  $\eta$ .

$$\theta = \theta - \eta \cdot \Delta_{\theta} \mathcal{J}(\theta; x; y) \quad (5.1)$$

The SGD optimizer updates a weight  $w$  in a way to reduce the loss function  $\mathcal{J}(w)$  and find the local minima of the parameters. As already mentioned this is one of the problems with pure SGD, it will very likely become stuck in a local minimum or saddlepoint, where one slope goes up and the other one down. Furthermore, it converges slower compared to newer optimizers [15, 45].

**Momentum**, first proposed in 1999 by Qian et Al. [38], can help to get faster to the local minimum. This is accomplished by an additional term which is added to SGD. A constant fraction  $\gamma$  is multiplied with the last parameter update  $v_t$  to  $\theta$ .

$$\theta = \theta - v_t \quad (5.2)$$

$$v_t = \gamma v_{t-1} + \eta \cdot \nabla_{\theta} \mathcal{J}(\theta) \quad (5.3)$$

Since the momentum term includes all previous updates 5.3, it allows the optimizer to accelerate in terms of speed towards the local minimum and thus converge faster.

This can be associated with a ball rolling down a hill. The momentum term increases as the ball rolls downhill accelerating in terms of speed, for subsequent gradients which pointing in the same direction. When the direction changes, the term decreases, the ball slows down. All in all this results in faster convergence and less oscillation or jumping around the minimum [45].

**Adaptive Gradients (AdaGrad)**, a newer algorithm proposed in 2011 by Duchi et

Al. [11], adapts the size of an update to the importance of the individual parameters. This is a great benefit for the occurrence of sparse data, which is the case for image data or word embedding tasks. It adjusts the learning rate term, by dividing the learning rate through the sum of previous updates w.r.t the network parameter  $\theta_i$  at time step  $t$ . An additional smoothing term  $\eta$  prevents the division by zero.

$$\theta_{t+1,i} = \theta_{t,i} - \frac{\eta}{\sqrt{\epsilon + \sum_{t=1}^t (\nabla_{\theta} \mathcal{J}(\nabla_{\theta_{t,i}}))^2}} \cdot \nabla_{\theta} \mathcal{J}(\theta_{t,i}) \quad (5.4)$$

This results in the learning rate decreasing when approaching a local minimum, meaning the overshooting problem is eased off. However, one weakness is the growing dominator, which makes the learning rate shrink to a infinitesimally small number until the step size almost dissolves to zero.

**Root Mean Squared Propagation (RMSProp)** extends AdaGrad's root squared loss function. It is an unpublished optimization technique proposed by Hinton et Al. [17]. The dominator takes, additionally to the past squared gradients, the current gradient at the current time step  $t$  is taken into account, weighting the last update more than the current. Hinton suggests to weight the last update with 90 and the current with 10 percent.

$$\theta_t = \theta_{t-1} - \frac{\eta}{\epsilon + E[g^2]_t} \cdot \nabla_{\theta} \mathcal{J}(\theta_{t-1}) \quad (5.5)$$

$$E[g^2]_t = (1 - \gamma)g^2 + \gamma E[g^2]_{t-1} \quad (5.6)$$

$$g = \nabla_{\theta} \mathcal{J}(\theta_{t,i}) \quad (5.7)$$

Unlike AdaGrad, RMSProp does not decrease monotonously, but can adapt the size of adaption. Now larger or smaller updates are possible in reference to their impact. Nevertheless, the issue with diminishing learning rates remains.

**Adaptive Moment Estimation (Adam)** [23], as well as AdaGrad or RMSprop, calculates adaptive learning rates w.r.t. the parameters  $\theta_i$ . As an extension it keeps track of an exponentially decaying average of past gradients  $m_t$ , as was already done in momentum.

Coming back to the visual anecdote, the ball has a lot of weight and is very heavy [45]. It prefers flat minima.

Past decaying average  $m_t$  and past squared errors  $v_t$  estimate the first momentum (the mean) and the second momentum (the uncentered variance).

$$m_t = \beta_1 m_{t-1} + (1 - \beta_1) g_t \quad (5.8)$$

$$v_t = \beta_2 v_{t-1} + (1 - \beta_2) g_t^2 \quad (5.9)$$

Since these terms are biased with zeroes, the initial updates are very small. Which is why  $\hat{m}_t$  and  $\hat{v}_t$  bias these terms:

$$\hat{m}_t = \frac{m_t}{1 - \beta_1^t} \quad (5.10)$$

$$\hat{v}_t = \frac{v_t}{1 - \beta_2^t} \quad (5.11)$$

This results in an update rule which reassembles RMSProp:

$$\theta_{t+1} = \theta_t - \frac{\eta}{\sqrt{\hat{v}_t} + \epsilon} \hat{m}_t \quad (5.12)$$

In particular, Adam makes use of two decay parameters  $\beta_1$  and  $\beta_2$ , referred as exponential decay rates. These parameters  $\beta_1$  and  $\beta_2$  are close to the constant  $\gamma$  term used in RMSprop and Momentum. The great advantage here is, that the learning rate can adapt in both directions solving the issue from AdaGrad or RMSProp of vanishing learning rates.

**Nesterov-accelerated Adaptive Moment Estimation (Nadam)**, now replaces Momentum with the better performing Nesterov accelerated gradient (NAG). It was first presented in 2016 by Dozat et Al [10].

**NAG** allows to approximately calculate the future position of the parameters. Referring back to Momentum, NAG is like a smarter ball, which knows that it has to slow down and not naively go up an upcoming slope again just to roll back down. NAG's first step is according to the last parameter update and taking the fraction  $\gamma$

into account. The second step approximates the future position of the parameters by calculating the loss function from  $\theta$  w.r.t. the previous update step. This step can be interpreted as a correction step.

$$\theta = \theta - \mathbf{v}_t \quad (5.13)$$

$$\mathbf{v}_t = \gamma \mathbf{v}_{t-1} + \eta \cdot \nabla_{\theta} \mathcal{J}(\theta - \gamma \mathbf{v}_{t-1}) \quad (5.14)$$

To combine Adam and Nadam, some steps must be done. We can write the gradient term as  $g_t$  and recall the Momentum update and parameter update function  $\theta_{t+1}$  with:

$$g_t = \nabla_{\theta_t} J(\theta_t) \quad (5.15)$$

$$m_t = \gamma m_{t-1} + \eta g_t \quad (5.16)$$

$$\theta_{t+1} = \theta_t - m_t \quad (5.17)$$

The 5.17  $m_t$  term can be extended with 5.16 resulting in ??:

$$\theta_{t+1} = \theta_t - (\gamma m_{t-1} + \eta g_t) \quad (5.18)$$

Momentum takes one step into the direction of the previous momentum update and another step into the direction of the current gradient. However, instead of the past Momentum vector, the current update rule is used in order to look ahead. Furthermore, expanding term 5.12  $\hat{m}_t$  with 5.10 and 5.10  $m_t$  with 5.8 results in the following:

$$\theta_{t+1} = \theta_t - \frac{\eta}{\sqrt{\hat{v}_t} + \epsilon} \left( \frac{\beta_1 m_{t-1}}{1 - \beta_1^t} + \frac{(1 - \beta_1) g_t}{1 - \beta_1^t} \right) \quad (5.19)$$

Where  $\frac{\beta_1 m_{t-1}}{1 - \beta_1^t}$  is the correction step of the first step from NAG. This term again, can be substituted by  $\hat{m}_{t-1}$  resulting in:

$$\theta_{t+1} = \theta_t - \frac{\eta}{\sqrt{\hat{v}_t} + \epsilon} \left( \beta_1 \hat{m}_{t-1} + \frac{(1 - \beta_1) g_t}{1 - \beta_1^t} \right) \quad (5.20)$$

As a final step the bias-corrected estimate of the momentum vector of the past time step  $\hat{m}_{t-1}$  is replaced with the bias-corrected estimate of the current momentum  $\hat{m}_t$  resulting in the optimization function for Nadam [45]:

$$\theta_{t+1} = \theta_t - \frac{\eta}{\epsilon + \sqrt{\hat{v}_t}} \cdot \left( \beta_1 \hat{m}_t + \frac{(1 - \beta_1) g_t}{1 - \beta_1^t} \right) \quad (5.21)$$

### 5.2.1 Experiments with optimizers

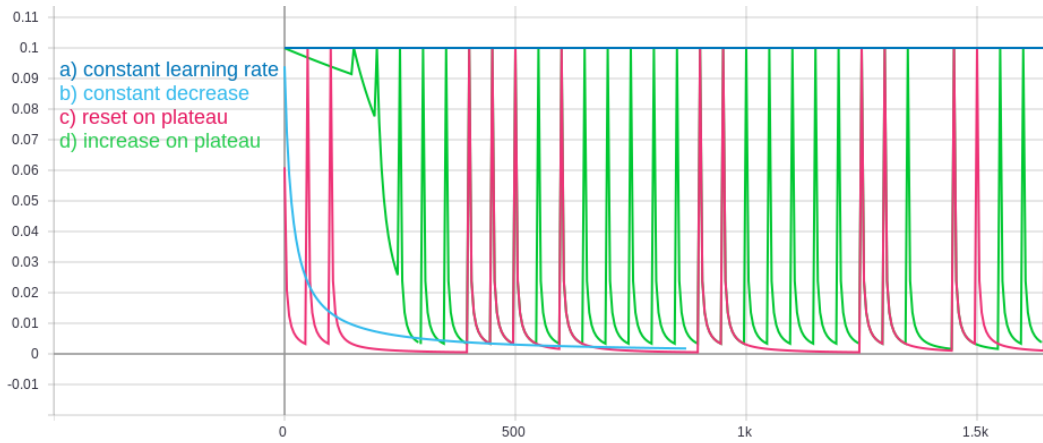


FIGURE 5.10: Learning Rate SGD.

In our experiments we tested SGD, Adam and Nadam all with initial learning rates of  $\eta = 0.001$ . We configured SGD to use Nesterov Momentum with a value of  $\gamma = 0.9$ , Adam with epsilon  $\epsilon = 1e - 7$  and AMSGrad. Nadam used the exponential decay parameters  $\beta_1 = 0.9$ ;  $\beta_2 = 0.999$  and epsilon  $\epsilon = 1e - 7$ . Additionally, we conducted several tests with the learning rate in SGD and its influence on the training process. One SGD configuration is with a constant learning rate  $\eta$  one is decaying by  $\eta = 0.01$  and one learning rate is decaying with  $\eta = 0.01$  but will reset to the initial learning rate, when no significant learning or changes regarding the loss value is observed over the last 50 epochs anymore. Another experiment with SGD increases the ascent of decay when a plateau is hit with increasing decay values  $[1e - 5, 1e - 4, 1e - 3, 1e - 2]$  as visualized in 5.10.



### Comparison of Adam, Nadam and SGD

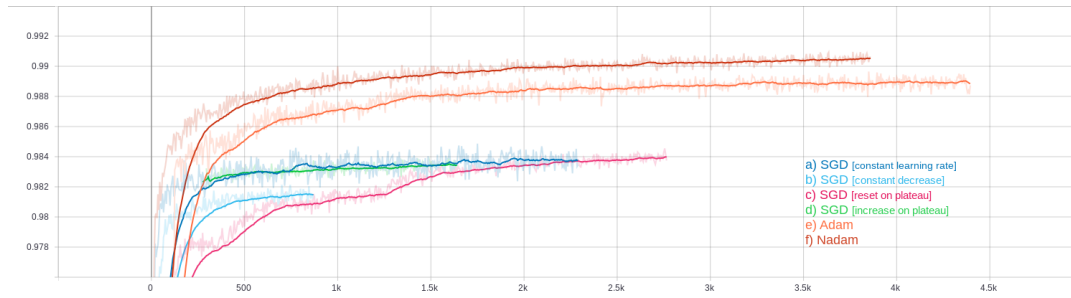


FIGURE 5.11: Accuracy

The Figure on accuracy 5.11 shows that our network makes huge learn progress in the first 200 to 300 epochs with an ascent of almost 90 degrees. However, the graph shows that SGD performs worse than Adam or Nadam, all networks reach a commendable accuracy above 98 percent, whereas Nadam even gets over the 99 percent mark. Adam and Nadam start to flatten a little bit later than SGD about 100 epochs. Furthermore, their curves flatten more evenly, whereas SGD seems to flatten more abruptly. Interestingly, the SGD optimizer, where we reset the learning rate on plateau, shows jumps in it's curve. There one can observe the typical flattening of SGD and then, when a reset took place, the learning process starts again. This indicates that SGD hit local minima from which it seems to jump out and re-trigger the adjustment of  $\theta$ .

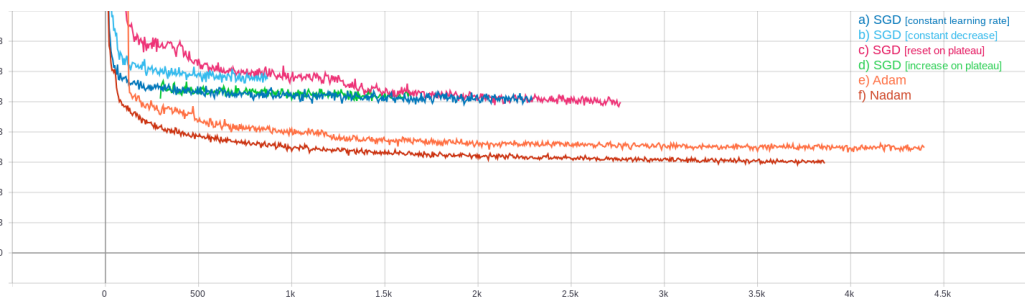


FIGURE 5.12: Loss

Similar process curve trends can be observed in 5.12, while the curves are mirrored at the x axis. This correlation of loss and accuracy trend proves the according learning process for the different optimizers.

## Conclusions

Our results are reflected by the research from Choi et Al [9]. They conducted a very interesting research with the thesis that more general optimizers would never underperform the ones they approximate. Meaning RMSProp, Adam and Nadam would always perform at least as good if not better than Momentum, Nesterov or SGD. They impose to carefully tune the hyperparameters and not just conclude an optimizer would work better than another one. This is why we used very commonly recommended hyperparameters. A continuing grid search could help to find an even more efficient way for training and probably even result in better learned network parameters  $\theta$ .

## 5.3 Performance of loss functions

As already mentioned in [section 5.2](#) loss functions  $\mathfrak{J}$  closely work together with optimizer algorithms. The loss function is used in the optimizer algorithm as seminal feedback deciding about the success of the learning process of a neural network. It calculates how close a prediction  $y_p$  from a neural network is to the true label  $y_t$ .

### 5.3.1 Commonly used loss functions

One classical loss function is Mean Squarred Error (MSE). The error represents the difference between  $y_t$  and  $y_p$ . MSE then squares the error to even negative results and calculates the sum of all these errors. For our fully convolutional network each pixel presents a certain class. As visualized in [5.9](#), our Human Parts module predicts nine classes. This means, there are nine label possible for each pixel. Now the neural network estimates with a certain probability how likely a certain class would be true for a specific pixel. The error then calculates the difference between the estimation or prediction and the true label, which includes a value of 1 only for the true class. Additionally to the sumation of squarred errors, MSE divides this sum with the number of all squares resulting in the mean value:

$$MSE(y_t, y_p) = \frac{1}{n} \cdot \sum_{i=1}^n (y_t - y_p)^2 \quad (5.22)$$

We trained the Keypoint Detection and Body Part Extraction modules with MSE.

However, with our Body Part Detection Module we initially had problems with class imbalances. First we conducted our training with Sparse Categorical Cross Entropy (SCCE), which is a common loss function used in image segmentation. Wrong predictions are weighed harder, especially the ones with a great wrong probability value. This is accomplished by calculating the logarithm of the predicted values. Since the logarithm function  $\log(x)$  is negative for  $x \in \mathbb{R}$  and  $[0 > x > 1]$  and input values closer to zero mean an exponential decrease towards  $-\infty$  and there is just one true label for the different classes of one pixel, if the prediction is clearly the wrong class, the cost will be exponentially higher.

$$SCCE(y_t, y_p) = - \sum_{i,j=1}^{i,j} y_{t_{i,j}} \cdot \log(y_{p_{i,j}}) \quad (5.23)$$

Here  $i,j$  stands for the column and row pixels of the image.

Nevertheless, our first results 5.14 made us believe that with SCCE our net was not able to learn the correct labels for the pixels. Especially the prediction after the 60th epoch shows, that the net mainly has learned to classify all body parts with the torso class. We assumed this was the case, because the likelihood of the pixel to be of class torso is higher than for example foot. Furthermore, however the accuracy graph shows descent results over 94 percent it started to flatten more and more becoming almost flat after the 50th epoch already.

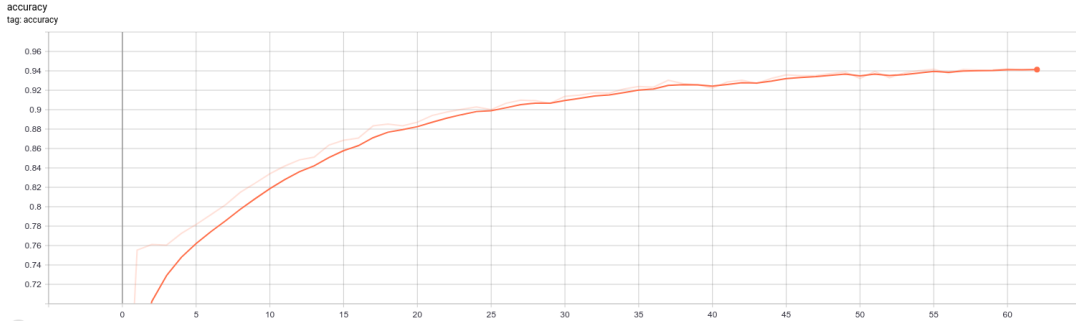


FIGURE 5.13: Accuracy for training with Sparse Categorical Cross Entropy loss function

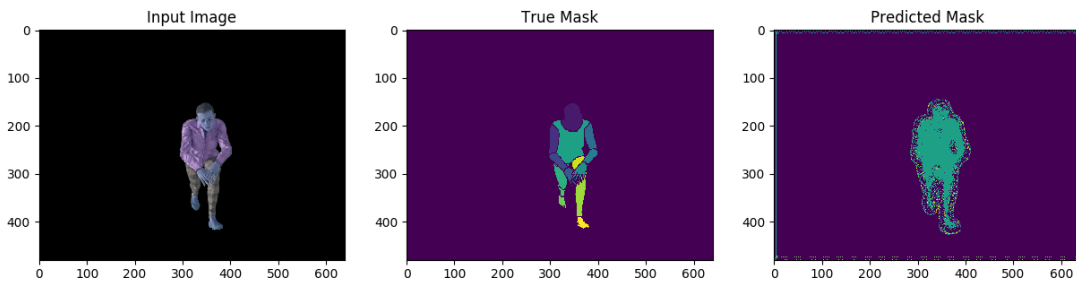


FIGURE 5.14: Predicted images for training with Sparse Categorical Cross Entropy loss function

We then created our own loss function for this class imbalance problem as explained in [subsection 5.3.2](#). Furthermore, we reduced the amount of classes from 14 to nine accumulating left and right body parts such as foot and arm. A later experiment however shows, that our build network HRNetv3 even learns slightly better than with our own created loss function CILoss [5.1](#). However, this of course could be by chance due to current training settings.

### 5.3.2 Our custom loss function CILoss

This loss function confronts the problem of class imbalance, which especially occurs in body part recognition. The background pixels appear most often, and the different body part classes occur much more less often and they even differ a lot in their relative occurrence.

We try to confront this problem with a weighed map  $\mu$ , which takes the body parts as a graph and calculates the distances from each body part  $b_x$  to all other body parts  $b_n$ , and store this data inside a table. This weighed map  $\mu$  is applied to the true labels

of  $y_{true}$  so that wrong predictions further away from the true class will be punished more. For example if the network predicts hand instead of lower arm, the error will be less as if the network predicts foot.

Additionally this weight map is evened out with a multiplier to reduce the distances and facilitate the learning process for the network.

As in MSE we calculate the difference  $\mathcal{E}$  between  $y_t$  and  $y_p$ , but do not square the result, we just use the absolute value. We multiply the resulting error  $\mathcal{E}$  with our weighed map receiving  $\delta$ . To calculate the loss we then sum the error and delta pixel-wise:

$$\mathcal{E} = y_t(x) - y_p(x)$$

$$\delta = \theta \cdot \mu[\operatorname{argmax}(y_t)]$$

$$L = \sum_{i=0}^n \mathcal{E}_i + \delta_i$$

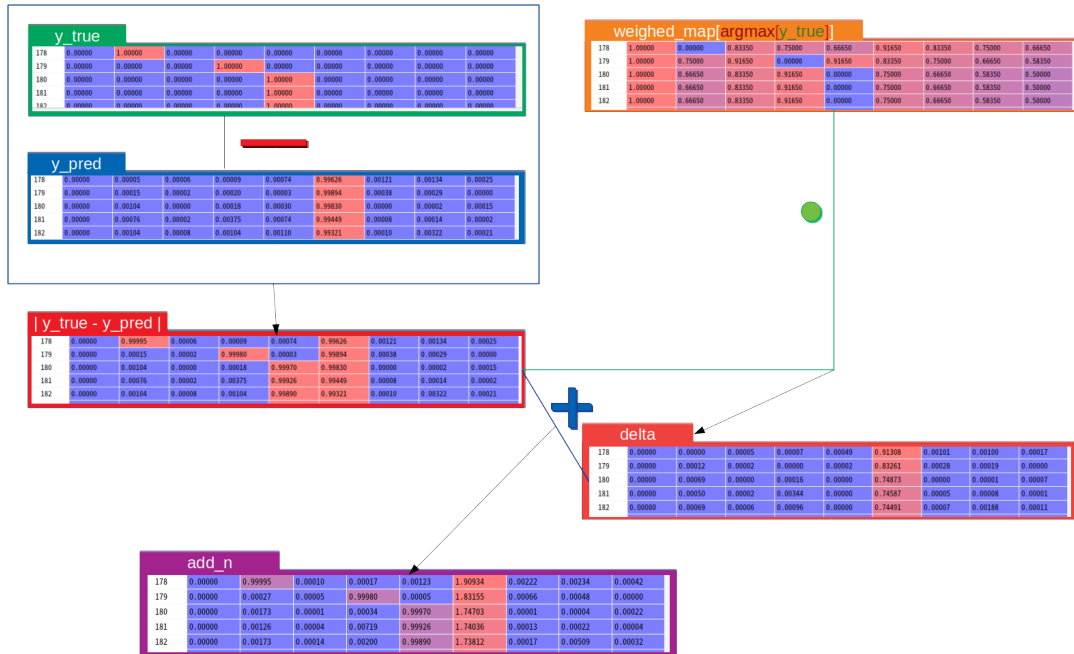


FIGURE 5.15: Visualization of our custom loss function CILoss



## Chapter 6

# Conclusion and future thoughts

Inspired by popular research from OpenPose, VidePose3d or Simulation of figure skating [5, 36, 67] which all have problems to correctly predict keypoints for spins in figure ice skating, we covered several analytical aspects such as motion capture, network architectures and the analysis of optimizer and loss functions.

We successfully created a new high resolution fully convolutional neural network HRNetv3, which includes state-of-the-art research findings from i.a. HRNet, HRNetV3, MobileNet [22, 48, 61].

Our architecture succeeded in predicting keypoints by learning from the synthetic dataset 3DPeople [37]. In sum we have built three modules for background extraction, human parts detection and keypoint recognition. These modules partly correspond to concepts used in other state-of-the-art research such as OpenPose, however our single ice skating domain specific background extraction module stands out other architectures.

For our applied research we have created a Python 3.7 project with Tensorflow 2 [52] as core library. We conducted our experiments in multiple Docker containers with the Tensorflow:*latest-devel-gpu* as base image [51] Moreover, we have spend lots of efforts to write good readable code with a decent OO-style following the SOLID principle. So our Github repository, which we plan to make publicly available, might help to promote further research in this topic. Especially, our feature driven approach making use of Github's feature pull request style and the formulation of proper commits helped us to iteratively improve our project architecture.

Since the data is one of the main aspects deciding whether a neural network learns the desired predictions, we looked into motion capturing as well, since we could not find an appropriate figure ice skating dataset for keypoint recognition. We took some captures with the inertial motion capture set from XSens. The setup felt very time-consuming and the cables all over the body connected to the battery and sensors felt very uncomfortable for recording on the ice. Additionally, multiple calibrations had to be done, probably because the system was not prepared for sliding movements. However, after the imposing capture, the integration into Blender and use of MakeHuman for creating a synthetic dataset became very promising. We especially value the diversity of data or video sequences that are possible from just one motion capture recording, which is why we are absolutely convinced that this is the way to gain decent data for an artistic sport such as figure ice skating. Yet, we think that in comparison to 3DPeople where random background images are put behind the person in action, even better results would be possible if an ice arena simulation was added to Blender producing even more realistic scenes. Another caveat we encountered when looking closely at the spins from figure ice skaters winning world championships such as Evgenia Medvedova or Alina Zagitova, we observed that these spins include a high level of motion blur. Nevertheless, our data from 3DPose included only image sequences without any blurriness, which is why we believe that predictions in the wild on spins such as the Biellmann with a lot of blurriness, keypoints could not be predicted accurately.

Throughout our research we spurned further ideas on how to continue in this topic of keypoint recognition. First, creating a decent synthetic dataset for figure ice skating adding motion blurriness and improving the recorded scene in Blender. Furthermore, test other motion capturing methods as for example the Awinda set from XSens, which could be much more comfortable and faster to apply, because the sensors are wireless, and no cables restricting movements on the ice, must be dealt with. Additionally, tests could be conducted with a markerless system such as Vicon [59].

Our network architecture could become more compact and better in performance by applying a grid search with multiple different parameters. Furthermore, the temporal information from a video could add additional information, allowing to faster and more efficiently predict videos as already argued in [39].



With this here presented study we try to further spur development and research in figure ice skating to further improve fairness in this sport. For example in[67] they simulated some figure ice skating figures and translated these to 3d animation. It would be very interesting to see, how skaters were rated, if the technical specialists and judges would see the animation, without knowing, who the skater was, or what the skater looked like. This could be a huge step in fairness. Furthermore, the rating could be conducted remotely, saving the jury from the cold ice rink and driving efforts. An even more advanced step to replace the necessity of jury, who are sometimes hard to get for a competition, would be another highly interesting research topic regarding action recognition. Another application would be the support during practice, with recommending actions to improve some jumps for example.

All in all the here presented research is meant to serve as foundation for further investigations towards action recognition in sports, especially artistic ones such as figure ice skating. Moreover, a very up-to-date topic on the writing of this paper are restrictions during the lock-downs of cities due to the COVID-19 (Corona) virus. Highly promising topics include as well physio therapy or feedback during fitness and dance routines.



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