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DEPARTMENT OF INTELLIGENT SYSTEMS
ÚSTAV INTELIGENTNÍCH SYSTÉMŮ

RUNNING MOTION ANALYSIS

SYSTÉM PRO ANALÝZU POHYBŮ PŘI BĚHU

TERM PROJECT
SEMESTRÁLNÍ PROJEKT

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Abstract
The goal of this thesis is to analyze body movement and gait while running. The system works with recordings from two cameras, one from the side and one from the front. The problem is solved using a skeleton detection tool based on the convolutional method.

Abstrakt
Cieľom tejto práce je analyzovať pohyb a držanie tela pri behu. Systém pracuje so záznamom z dvoch kamier, zboku a spredu. Využíva nástroj na detekciu skeletu založenú na konvolučnej metóde.

Keywords
artificial intelligence, neural networks, computer vision, skeleton detection, running form, running, running gait, AI, movement detection, body position, camera, biometrics, Python, Anaconda, PyTorch, kinematics, video

Klíčová slova
umelá inteligencia, neurónové siete, počítačové videnie, detekcia skeletu, bežecká forma, beh, držanie tela, detekcia pohybu, pozícia tela, kamera, biometrika, Python, Anaconda, PyTorch, kinematika, video

Reference
ELIÁŠ, Radoslav. *Running Motion Analysis.* Brno, 2020. Term project. Brno University of Technology, Faculty of Information Technology. Supervisor Ing. Tomáš Goldmann,

Running Motion Analysis

Declaration

Hereby I declare that this bachelor's thesis was created solely by me, under the supervision of Mr. Ing. Tomáš Goldmann. Every source and publication used in this thesis is properly cited and included in the list of references.

. . . .
Radoslav Eliáš
January 24, 2021

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Contents

Chapter 1

Introduction

Sports and exercise are an essential part of staying healthy and keeping our bodies working properly. According to the World Health Organization, one in four people is physically inactive, causing diseases and shortening life expectancy up to 10 years.[7]

Introducing people to exercise is now more important than ever. Walking and running could be considered as some of the simplest, yet most efficient activities available for beginners. Most people already have all they need to start running, but with the vast availability of this sport comes the problem of proper technique and safety. Bad form can inflict unnecessary knee pain and many more injuries, caused by too much pressure being applied to joints, ligaments, and tendons.

While medicine and mainly physiotherapists can fix these issues, the average beginner runner usually doesn't bother seeking professional help until it's too late and some damage has already been done. The goal of this paper is to automatize this process by analyzing video recordings and make it accessible to anyone. With smartphone cameras improving every year, a system like this will enable any person to record himself and adjust his running form which will eventually lead to injury prevention.

Chapter 2 focuses on biomechanics as a study and further dives into running, gait, and body position. It talks about the essential parts of a good running posture and how they help prevent injuries and other health problems. The next chapter 3 presents the basics of neural networks, standard methods of computer vision, and how they're used to detect and track human pose from a video. Afterwards, the main focus is joint extraction and position comparison to other body parts.

Personally, this topic is very important to me as a passionate runner, which is why I want to help other people discover the beauty of my sport by minimizing the risks involved.

Chapter 2

Human biomechanics and running analysis

2.1 Biomechanics

Biomechanics is the study of the structure, function, and motion of the mechanical aspects of biological systems [8]. It basically means that this field studies how all animals and humans move, how their bodies function, and why we are able to just stand up from our desks and walk to the nearest coffee shop. The ability to do that is called the **locomotive function**. This chapter will focus specifically on human biomechanics. We, as a species, have a big range of movements and postures that we are able to perform. All these functions are parts of human biomechanics.

The main real-world application of this study is physiotherapy, which aims to improve physical performance and prevent or recover from movement-related injuries.

2.1.1 Terminology

Parts of this section are paraphrased from [3].

Human biomechanics studies forces affecting human muscles and bones and how the body tissues respond to these forces. They can be divided into 2 different groups, internal and external. External forces are caused by an outside environment for example the ground pushing onto a foot as a person takes a step. Most of them are contact forces, which means that the object applying the force is in contact with or touching the human body. Internal forces are generated by the body itself therefore the name. This paper will mostly work with external ones.

Furthermore, biomechanics are split into static and dynamic concepts. Considering the topic being running motion, we will talk about the dynamics. They study the conditions under which an object moves.
There are 2 types of dynamic concepts:

- Kinematics
- Kinetics

Simplified, kinematics study and describe the motion of an object without referencing the forces causing said motion, e.g. football rolling from place A to place B. In contrast, kinetics take those forces into consideration, e.g. player kicking the football causing that movement.

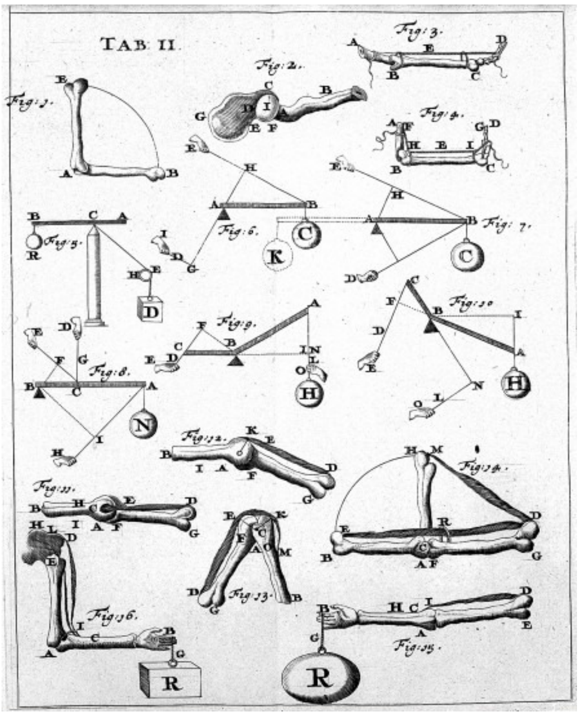


Figure 2.1: Sketches by Giovanni Alfonso Borelli in 1680, showing first studies of biomechanics

2.1.2 Kinematics

There are five variables studied in kinematics [10]:

- Type
- Location
- Direction
- Magnitude
- Rate

Type of motion can either be linear, which means all the body parts are moving in the same direction along a straight line, or angular. Angular motion is in other words rotation around axis.

Location of joint is usually defined in a system of anatomical planes and axes. There are three planes of motion. Sagittal, transverse (sometimes referred to as horizontal), and frontal. Shown in 2.2.

Direction of motion is also described by the three basic planes of motion. Flexion and extension are the two opposing directions in the sagittal plane. Flexion motion decreases an angle between two body parts while extension increases them. When a motion reaches extreme on one side of the range it's often referred to as *hyper*. In the frontal plane, the main movement is called abduction which goes further away from the midline of the plane. Its opposite is adduction, in other words moving back towards the midline. The most common motions in the transverse plane are internal and external rotations.

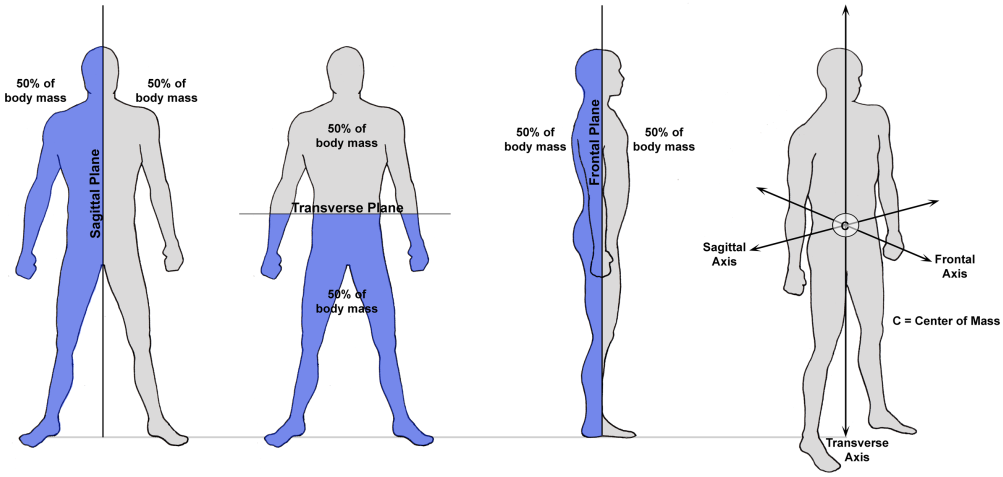


Figure 2.2: Three planes of motion, source:[5]

For linear motions, **magnitude** represents the distance between two spots that the object traveled. Magnitude in angular motions is measured in radians or degrees.

Rate of motion is in other words speed or velocity of the studied object. Sometimes acceleration is also one of the variables looked at.[11]

2.1.3 Kinetics

As stated before, kinetics studies the forces that cause the motion of an object. Force can be described as an act of one object to another and can be either internal or external. In order to determine how will the object or a human body, in this case, react, all existing forces must be taken into consideration or the result will not be precise.

Well known Newton's laws also describe the kinetics of an object. Law of inertia or in other words Newton's first law states, that the higher the mass the stronger the force needed to transpose an object from a standstill to a moving motion. Newton's second law shows that a number of forces will affect an object to increase or decrease its velocity depending on the direction of the forces. The third law states that for every action there is an equal reaction. A simple example in running is that a runner will run faster on a concrete road than in sand with the same effort because the concrete will create a bigger reaction or „pushback". [3]

2.1.4 Application

Biomechanics essentially study movement technique, which is most often applied in sports. The goal is usually either one of two things. Either to prevent injuries or at least reduce the risk of them or to improve performance by adjusting or removing unnecessary movements. There are a few different areas where biomechanics are applied [13]:

- The identification of optimal technique for enhancing performance
- The assessment of muscular recruitment in order to prevent overloading
- The analysis of body loading to determine the safest method of performing exercise

- The analysis of sports equipment e.g., shoes, bicycles, rackets.

2.2 Biomechanics in sports

Center of Gravity

Center of Gravity or COG for short, is an imaginary point around which body weight is evenly distributed. This concept is important to understanding stability, balance, and their effects in sports with rapid body movements. The Base of Support is an area beneath an object which includes every contact point of the said object and a surface. COG changes often and when the line of gravity falls outside the Base of Support, adjustment is needed to stay balanced. [11]

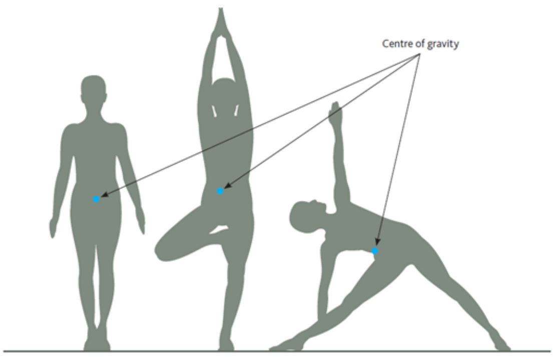


Figure 2.3: Center of Gravity, source: [19]

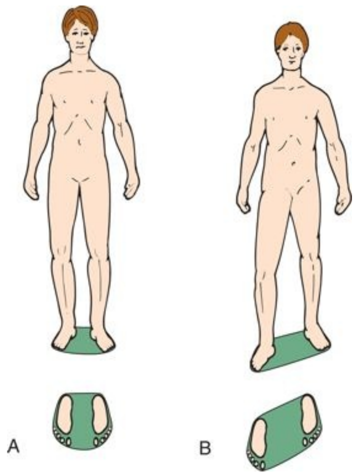


Figure 2.4: Base of Support, source: [3]

Balance

Balance is the ability of a person to control his or her stability. Simplified, it means keeping the body under control and moving only where the person wants to.

Static Balance

We talk about static balance when the body is stationary. It's the ability to maintain a fixed posture while at standstill.

Dynamic Balance

Dynamic balance is much more demanding and problematic. Developing babies learn this later than static balance. It consists of keeping the center of mass over the base of support at all times while constantly changing body position and with it, the center of gravity. Athletes like gymnasts need to perfect this skill to perform in their field.

Momentum

Momentum is the product of an object's velocity and mass and is closely linked with Kinematics. Basically, it's the quantity of motion. Momentum can be transferred between objects [11]. There are 2 types of momentums.

Linear Momentum

As the name suggests, linear momentum is in a straight line like running, walking, or cycling in one direction.

Angular Momentum

Angular or in other words rotational momentum is created by said rotations of objects. A good example of this is tennis and how good players often don't hit the ball perpendicular with a racket but with a slight angle which creates more power.

2.3 Running analysis

Running while similar to walking has a few key differences crucial to understanding proper technique and injury prevention. Each person has different flexibility, strength, and body composition. When determining proper running posture, it's important to take all these variables into a consideration. Fatigue plays a big role too because it's harder to focus on body position when muscles are getting tired. Here are a few of the most common problem areas contributing to incorrect running technique [14].

Feet

Starting with the most obvious, feet are the only contact point with the ground while running. That means they take the biggest abuse and are very prone to damage and injuries. When running, a person should hit the floor with the ball of the foot. The two most common problems are striking with toes or with the heel. These may not be harmful after one or two runs, but in the long term can cause a lot of pain. A less common but still existing type of bad foot placement is hitting the ground on an angle - both left and right sides of the foot should hit the surface at the same time. Another incorrect gait type is when the front of a foot points slightly either outwards or inwards. It should always follow the direction of the movement of a person in a straight line.

Legs and Knees

Effects of legs and knees are closely related to feet position discussed earlier. When running, it's important to move legs in a straight line, the same as with feet. Every stride should be done with the shin being perpendicular to the surface, or at least as close to perpendicular as possible. Inconsistence in this particular position causes the aforementioned heel or toe striking. When the angle of the shin is too big, the heel drops first and hits the ground before the rest of the foot. Otherwise, if the angle is too small the toes might get damaged by the repeated load.

Torso

Torso makes up the biggest mass of the human body, so using it properly can greatly increase one's performance. The Center of gravity is also situated here while running, meaning that even a slight movement will cause big changes in effectiveness. Again, common problems are leaning too far forward or too far backward. Even though the torso should be fairly straight, a slight lean forward will drive the body in that direction. But when it's overdone, hips have a limited range of motion, and the bigger the lean forwards, the more of that range we lose. On the opposite end, when leaning backward the body needs more power to actually move in the wanted direction. Still, the torso shouldn't be totally static while running, but should slightly rotate with every stride.

Shoulders and Arms

The upper body is usually not the part people think about when talking about running, but a simple test of sprinting with straight arms attached to one's torso shows how much speed actually comes from this part of the body. Similarly to the torso, shoulders and arms should move with every stride but in a sort of „X" pattern. Meaning that with the left foot forward, the right shoulder and arm should come forward, and the other way around. Shoulders should be relaxed as not to waste energy but slightly pulled back, almost as squeezing a pencil between shoulder blades. Arms should be close to the torso, bent at a 90-degree angle in the elbow. Moving them slightly up and down with every stride helps with driving the body forward, almost as pushing itself in the direction it's headed.

Head

The head is the brain of the body, obviously. We naturally move in the direction our eyes are looking. That's why looking at our feet may cause the torso to lean forward, the shoulders hunching over, and so on. Focused gaze makes or breaks proper posture while running. Ears should be aligned with the shoulders.

2.3.1 Running gait cycle

The running gait cycle can be described as a series of movements, that combined together, create one repetition of a running motion. It starts with one foot hitting the ground, goes through launching forward from that position and striking with the other foot, and finishes where it started, hitting the surface with the first foot. This is called one gait cycle and repeating it creates the running motion. There are three key positions in the gait cycle: Initial contact, mid stance, and mid flight. Check 2.5 for visual representation.

2.3.2 Form analysis in clinical environment

Analyzing running form and posture most commonly occurs in a physical therapist's clinic. There are two different approaches to this.

The first is when the runner is jogging on a treadmill and the physical therapist observes in real-time. The advantage of this type of analysis is the immediate actions that can be taken. Small adjustments in the technique can be observed in the same session, thus the ability to experiment with different problem fixes, etc.

The other approach is when the running is recorded with a camera and the video is then analyzed. This approach also creates advantages, for example, the possibility of multiple therapists assessing the running technique, without the need of them being at one place at the same time. The video can be sent by the patient even without visiting the clinic, although more common is recording the video there. The main reason for this is the importance of precise camera set up to ensure good visibility of body parts of interest [18]. Running recording is usually performed on a treadmill, in order to eliminate surface inconsistencies like potholes and such. Two cameras are used more commonly, one from the side and one from either the front or back of the runner. Each view shows different aspects of running posture, which is the reason why one would be incomplete without the other. For example, the frontal view will not show anything about torso lean or knee flexion angle [6]. Higher framerates are desirable in cameras when recording running because they enable slowing down the videos and examining it frame by frame.

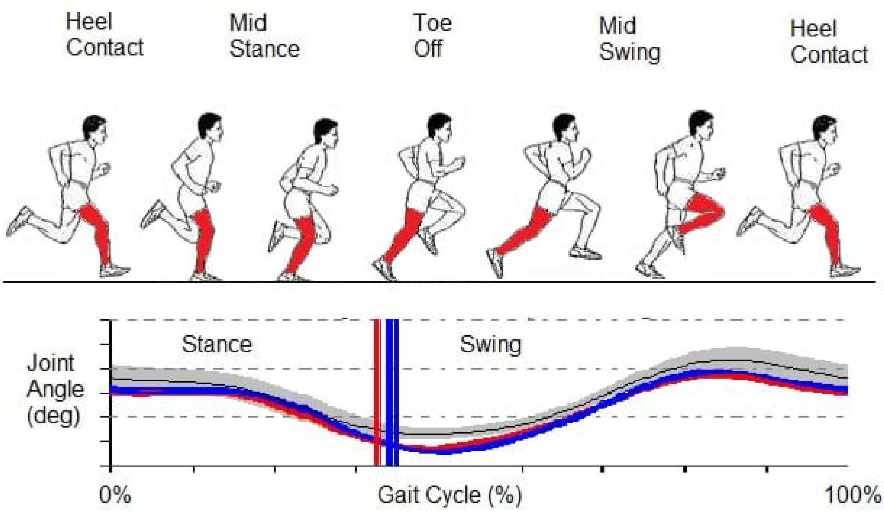


Figure 2.5: Running gait cycle, source:[2]

In 2016, a study [18] was made by the University of California in San Francisco with an objective to create a framework for systematic video-based running analysis. Testing and analysis were performed on athletes with confirmed running-related injuries.

The runners were recorded while running on a treadmill after a warmup with two cameras. One from the side and one from the posterior view. Colorful markers were applied to some parts of their clothing in order to catch movements that would otherwise be hidden by the wardrobe.

Variables of interest like angles or distances between body parts were then identified visually on a slow-motion video. Each position of the running gait cycles is used for different kinematic variables and correct identification of these moments is crucial for an accurate evaluation of the running gait.

Side view

From the side view, these variable were studied:

- Foot Strike Pattern

- Foot Inclination Angle at Initial Contact
- Tibia Angle at Loading Response
- Knee Flexion during Stance
- Trunk Lean
- Overstriding
- Cadence

Proper technique in most of these was discussed in 2.3. Overstriding is the result of combining multiple of these variables causing footstrikes far away from the base of support. The correct cadence is still unclear to scientists, but the estimations are around 180 steps per minute. Lower cadence can lead to overstriding and health problems that come with it.

Posterior view

- Base of Support
- Heel Eversion
- Heel Whips
- Knee Window
- Pelvic Drop

The posterior view mainly focuses on heel positioning and movement with a few other variables. The Knee window is basically the space between knees. Ideally, the window should be as small as possible while the knees never touch. Pelvic drop is identified in the stance phase from the markers applied to the runner's body. It's the position difference between the marker on the stance leg and the marker on the swing leg demonstrated in 2.6. An excessive pelvic drop may lead to injuries.

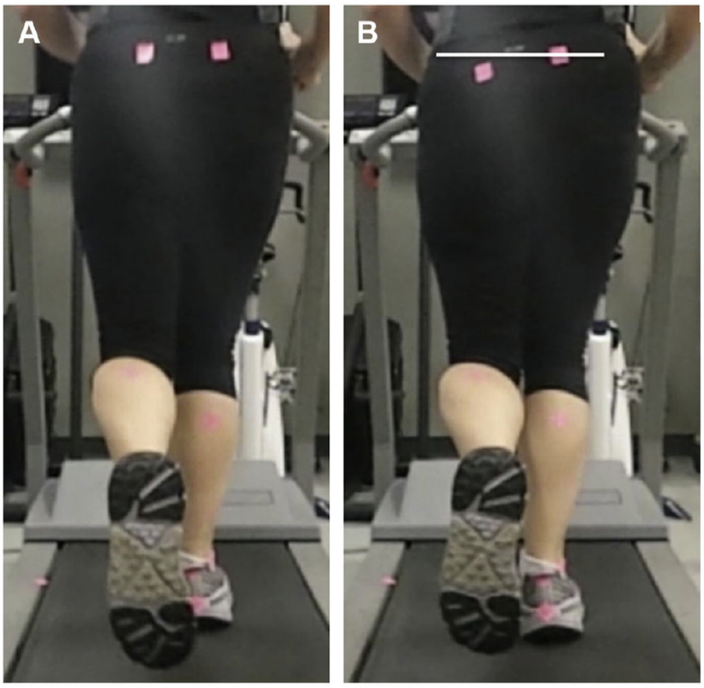


Figure 2.6: Pelvic drop analysis, source:[18]

Chapter 3

Human pose detection from video

The scientific field of **Computer vision** deals with the problem of detecting objects from a static image or a video recording. Computer vision is a subset of a much larger field, the **Artificial intelligence** . The goal is to understand and analyze digital images from the real-world in order to create numerical data that make sense to computer processors. The automatization of all the complex abilities, that the human visual system has, opens up many possibilities. Common problems solved using computer vision are scene reconstruction, video tracking, object recognition, image restoration, motion estimation, and others [1].

3.1 Neural Networks

Neural networks or NNs for short are the standard systems used in artificial intelligence. They are massive, parallel computing systems consisting of a huge number of intertwined simple processes. The name and the inspiration behind these are the biological neural networks that make up an animal brain. Neural networks have the ability to learn, which makes them the ideal tool for analyzing unknown inputs. Information in this section is taken from [12].

Biological neuron

A neuron, in the biological context, is a cell with the ability to process information. A single neuron consists of multiple parts, each with its signature role and function. These are shown in Figure 3.1:

Neuron accepts a signal from other neurons, processes data from the input and creates a new modified signal which is then forwarded to other neurons.

The nucleus works as a storage for information about the neuron's traits. Dendrites are basically receivers for all incoming signals and the axon is a transmitter for the final signal generated by the cell's body. Axon at the end branches into multiple strands. The place of contact between one neuron's dendrite and another neuron's axon strand is called a synapse.

Chemicals called neurotransmitters are released when an input reaches a synapse. These can adjust the effectiveness of a neuron, enabling humans to learn and remember history.

Every neuron is connected with about $10^3 - 10^4$ other neurons. The frequency of communications between units is only a few hundred Hertz, meaning it's much slower than a modern computer processor. And yet, the human brain performs complex tasks like face

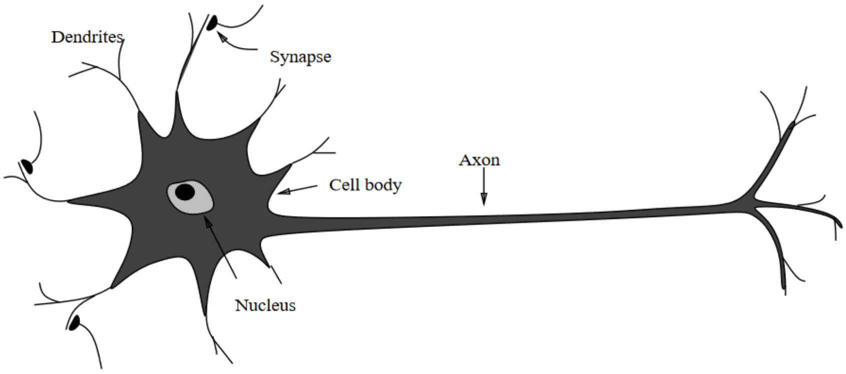


Figure 3.1: Biological neuron, source:[12]

recognition in just a few milliseconds. In conclusion, the brain runs a parallel program about 100 steps long.

Computational model

The first computation model of a neuron was created by two scientists called McCulloch and Pitts. This model computed the weighted sum of multiple inputs and compared it to a threshold value. The output was either „1“ or „0“, depending on the comparison with the threshold. This model had a few limitations and differences with the biological neuron. For example, using threshold values instead of graded responses and the lack of asynchronous updates of the neuron [12]. It was later generalized into a model called **perceptron**, shown in 3.2.

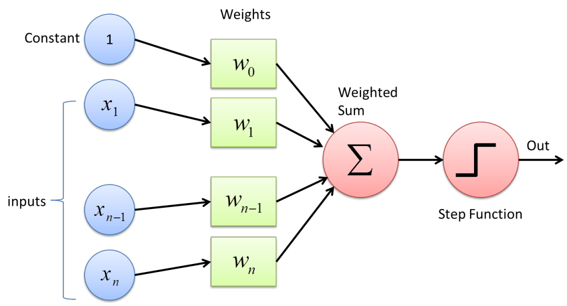


Figure 3.2: Perceptron - computation model of a neuron, source:[17]

Correlations between the two models are:

- Synapses = Weighted sums
- Dendrites = Input wires
- Axons = Output wires
- Cell body = activation function

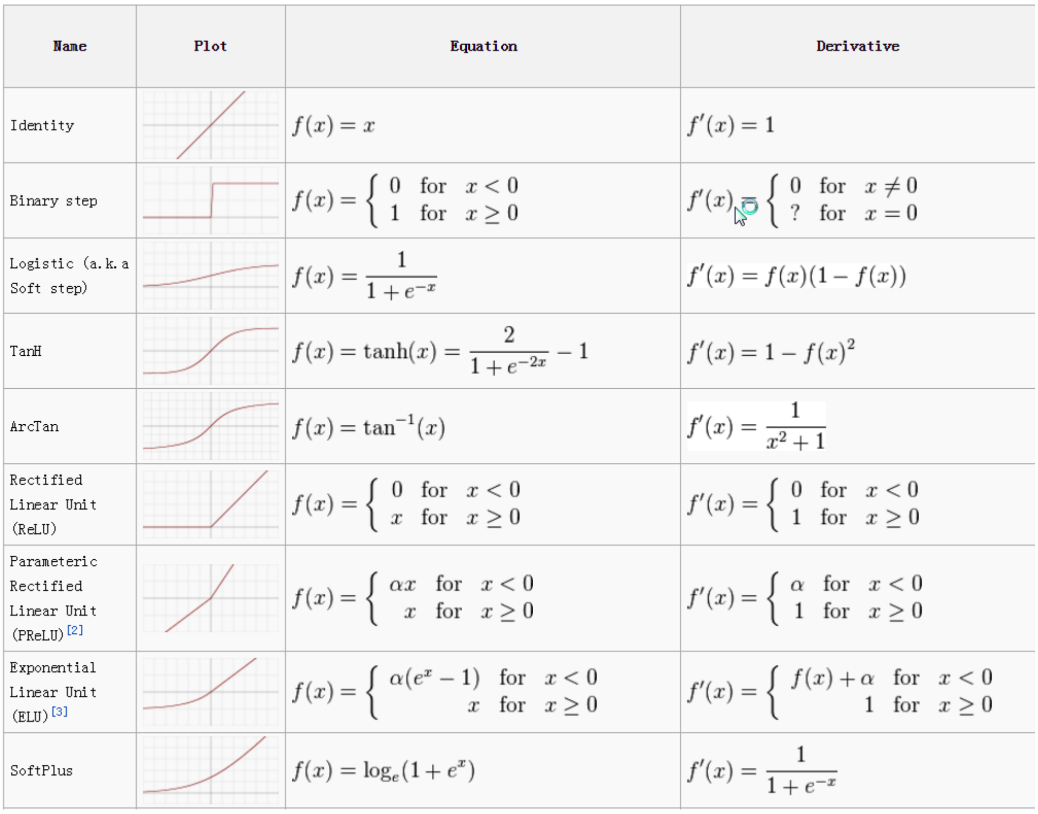
The mathematical model of a neural network is as follows.

$$y = f(b + \sum_{i=1}^{n} w_i x_i)$$

Where **b** is bias, **n** the number of inputs, **w** are the weights of corresponding inputs, and **f** is the activation function.

Activation function

Step function or activation function determines the output of a single neuron. These can be split into two categories, linear and non-linear. The activation function basically maps the output value in some specified range, depending on the type of the function. Most commonly used step functions are listed in 3.3.



Name	Plot	Equation	Derivative
Identity		$f(x) = x$	$f'(x) = 1$
Binary step		$f(x) = \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} 0 & \text{for } x \neq 0 \\ ? & \text{for } x = 0 \end{cases}$
Logistic (a.k.a Soft step)		$f(x) = \frac{1}{1+e^{-x}}$	$f'(x) = f(x)(1 - f(x))$
TanH		$f(x) = \tanh(x) = \frac{2}{1+e^{-2x}} - 1$	$f'(x) = 1 - f(x)^2$
ArcTan		$f(x) = \tan^{-1}(x)$	$f'(x) = \frac{1}{x^2+1}$
Rectified Linear Unit (ReLU)		$f(x) = \begin{cases} 0 & \text{for } x < 0 \\ x & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$
Parameteric Rectified Linear Unit (PReLU) [2]		$f(x) = \begin{cases} \alpha x & \text{for } x < 0 \\ x & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} \alpha & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$
Exponential Linear Unit (ELU) [3]		$f(x) = \begin{cases} \alpha(e^x - 1) & \text{for } x < 0 \\ x & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} f(x) + \alpha & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$
SoftPlus		$f(x) = \log_e(1 + e^x)$	$f'(x) = \frac{1}{1+e^{-x}}$

Figure 3.3: Commonly used activation functions, source:[15]

Weight initialization

Weight initialization is the process of determining weight values and biases before the training phase of the network. Correct initialization has a big effect on how fast the network can learn. Bad starting weights can lead to never reaching the required accuracy of the neural network [16].

With zero knowledge of the final system, there are two possible techniques of initialization. Either setting all the biases and weights to zeroes or random numbers. With zero initialization, the biases have no effect on the outcome. Zero value weights, on the other hand, will cause symmetric relations among units and therefore all the weights will be exactly the same in all other iterations.

Random initialization solves this problem which is why it's used more commonly. But with it, comes the issue often referred to as the **vanishing gradient**. When the starting weights are initialized at very high values, the activation function maps them near the value „1“. This causes the weights to change very slowly and ultimately the learning takes a lot of time. Equally, the same phenomenon happens with weights initialized with low values mapping them close to „0“ [16].

To avoid this issue, the used initialization technique needs to be compatible with the activation function of the neural network. There are two commonly used methods nowadays, he technique and Xavier initialization.

He method is used with the **ReLu** and **leaky ReLu** activation functions. First, random numbers are generated for each weight and then every value is multiplied by $\sqrt{\frac{2}{n_{in}}}, where\ n_{in}$ is the number of input signals.

Xavier technique is a modification of the previous initialization. The procedure is the same, but with the multiplication value being either $\sqrt{\frac{1}{n_{in}}}\ or\ \sqrt{\frac{1}{n_{in}+n_{out}}}, where\ n_{out}$ is the number of output signals.

Neural Network Learning

Information in this section is paraphrased from [12]. The learning process of a neural network can be described as a process of updating the architecture of a network to perform a specific task efficiently and precisely. The weights of the inputs are changed iteratively according to the data fed to the network. The ability to learn is the key feature of how we are able to simulate the human brain.

Unsupervised training

The simplest way of training a network is called unsupervised. The data are fed into the network without any hints about which input pattern is correct. A network trained this way will split data set into groups with similar characteristics. The number of output chunks can be set before the training.

Supervised training

With supervised training, every input pattern carries information whether it's correct or not. The network calculates output for a pattern and compares it with the expected result. How much these two differ dictates the error of the network. The weights of the network are then altered according to the error to match the correct output as closely as possible. This process is repeated until the error value is lower than the predefined deviation. This is also often referred to as learning with a teacher.

3.2 Human pose detection

Human pose tracking is a rapidly evolving field and a focus of interest of many researchers.

In 2017, a benchmark with a corresponding dataset for pose estimation was created by scientists at Cornell University [9]. This benchmark was published by a community-driven webpage called „Papers with Code“ [4]. Many state-of-the-art up and coming frameworks for pose detection were submitted for testing. The results were then sorted by two variables: **MOTA** or Multiple objects tracking accuracy and **mAP** or mean average precision. Frameworks with the highest MOTA are illustrated in 3.4.

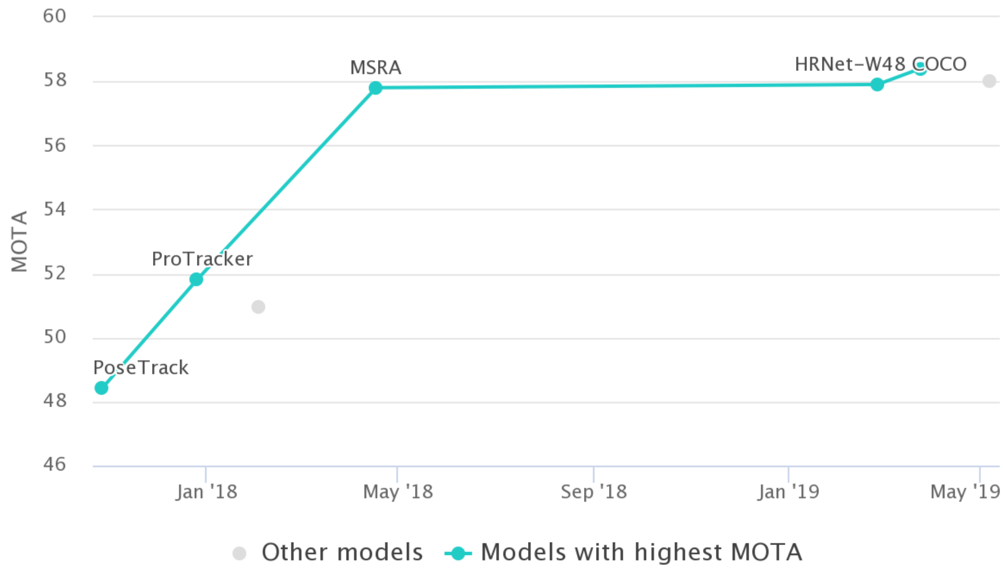


Figure 3.4: Graph showing MOTA performance of frameworks on the PoseTrack2017 benchmark, source:[4]

For running motion analysis, MOTA isn't as important because there's usually only one moving object in running videos.

3.2.1 LightTrack

3.2.2 STAF

3.2.3 HRNet-W48 COCO

3.2.4 MSRA

Chapter 4

Conclusion

Chapter 2 talks about the laws of biomechanics and how they're applied in sports. Furthermore, it specifies the proper running technique, posture, and their correlation with injuries, efficiency, etc. Lastly, the ways of analyzing running in a clinical environment by physical therapists are discussed.

Chapter 3 serves as an introduction to the field of Computer Vision. The main topic is neural networks, their basics, and real-world applications. The computational model of neural networks is defined here, with all of its parts like activational functions. The next section talks about human pose detection and state-of-the-art algorithms that deal with this problem.

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