**Seminar Artificial Intelligence 2002: “Artificial and natural walking machines”**

# Rapid Locomotion

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# 1 Introduction

## *1.1 Allday life experience*

Lets start with this piece of allday life experience, that everyone might know: Imagine yourself walking between your home and your working place. Suddenly, you realize, that you are a little late. You start walking faster. But you still are walking. You walk faster and faster, suddenly, you break into a run.
We might to considerate this from a phenomenological point of view: We know, that observing a person that is running looks quite different than a person that is just walking. It is also clear, that while running, the trunk or maybe your whole body moves more, one could say it jerks. Moreover, one needs more power while running, and gets more tired running the same time as just walking, but in exchange, one moves faster than just by walking.
So the Question might arise: Why running?
At first thought, one might think this is a stupid question; Changing from walking to running is natural, humans and animals just do it by themselves. Viewed from its primary purpose, one runs because it enables faster locomotion than just by walking.

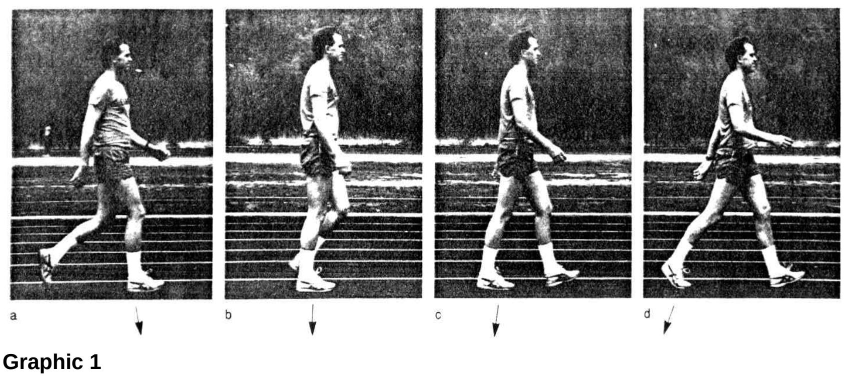
## *1.2 Covered issues*

We want to have a little closer look at that. We ask ourselves: What advantage does it have, if one changes gait so dramatically to travel faster. Wouldn't it also be possible to move faster keeping the same gait? How does it work to locomote rapidly? What are mechanisms that are used in nature to support this and what are problems one must considerate when trying to build rapid locomotion systems. We also will have a look at the implementation of rapid locomotion in AI-projects.

# 2 Theoretical background

## *2.1 Walking, running and its differences*

### 2.1.1 Walking in humans




Graphic 1

Graphic 1 (Alexander, 1984b) shows a human walking. The full stride is divided into 4 stages (a – d) displaying the position of the limbs and the moves. The arrows show the force exerted on the ground. Every stage will be described as follows, according to Alexander (1984b):

**Stage A**

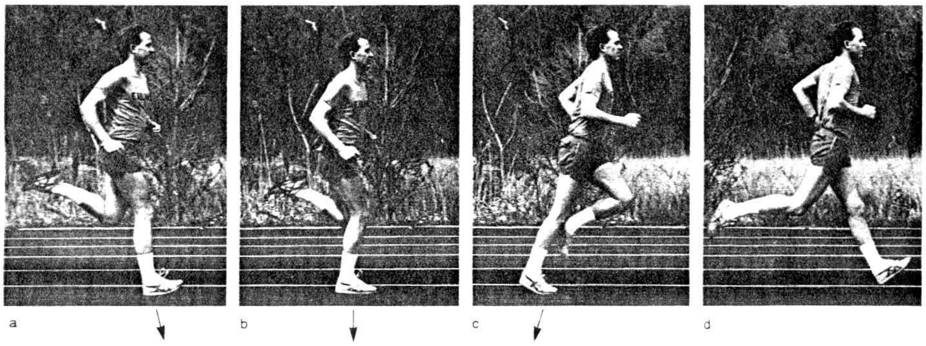
The supporting leg is slightly bent, nearly all the bodyweight is on that leg. The other leg reached its backmost position in swinging backward and starts to swing forward.

**Stage B**

The supporting leg is fairly straight, center of mass is vertically above the supporting foot. The trunk is highest at this stage. The other leg passes the horizontal position of the supporting leg and is bent.

**Stage C**
Center of mass is shifted forward. The supporting leg is still almost straight while the other leg swings forward, gets stretched prepared to be put on the floor.
**Stage D**
The other leg touches the ground. The former supporting leg swings backward, the sole is lifted. Center of mass is about between both legs while the trunk is lowest at this stage.

### 2.1.2 Running in humans

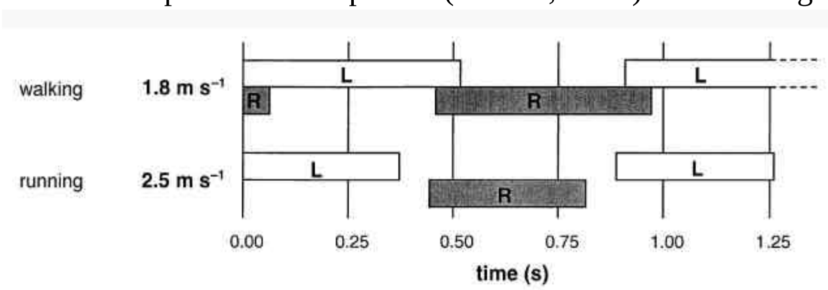


Graphic 2

Graphic 2 (Alexander, 1984b) shows a human running. Analogous to chapter 2.1.1 Walking in humans, the stride is divided into 4 stages. Also, the arrows show the forces exerted on the ground.
Every stage will be described as follows, according to Alexander (1984b):
**Stage A**
The supporting foot has just been put on the ground, the back leg swings backward.
**Stage B**
The supporting leg is bent, the trunk passes over the supporting foot and is lowest at this stage.
**Stage C**
The trunk is shifted forward, the hind leg is swinging forward in a quick movement: The supporting leg is stretched again (important).
**Stage D**
Both feet are off the ground, the trunk is highest at this stage. Most of the distance is covered in this stage, which can be described as the actual leap.

### 2.1.3 Main differences

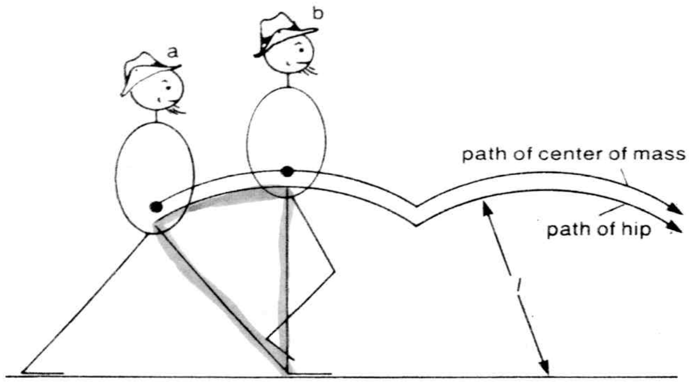
The contact pattern in Graphic 3 (Minetti, 1998) shows the ground contact of the feet over



Graphic 3

time. In walking, sometimes both feet are on the ground simultaneously but never off the ground at the same time, while every foot touches the ground for more than 50% of time
In running, sometimes both feet are off the ground, but never on the ground at the same time, while every foot touches the ground less than 50% of time. (Alexander, 1984b)
As we also remark, that there‘s a certain speed at which the change from walking to running occurs. It‘s normally about 2.5 m/s (about 9km/h). This speed depends on a few factors, but one can predict it quite well. We‘ll have a closer look, why it is like that.

## 2.2 Simple model




Graphic 4

In Alexander (1984b), a simple model is described that tries to explain, why gait is changed at a certain speed. This is also shown in graphic 4. Some simplifications have been made in this model:
The supporting leg is always straight. Legs can be bent when passing over at stage b, (referring to stages of graphic 1) otherwise, it would hit the ground and couldn't be shifted.
The legs have no mass in this model. Therefore, the center of mass of the body occupies a fixed point in the trunk and moves along arcs of the same radius as the path of the hip joint.
The mans walking speed is v. Its legs are of the length l. Using a formula from mechanics, we can say that a point (in this case the center of mass of the person) that is moving with speed v along an arc of a circle with radius l is accelerated with v2/l towards the center of the circle.

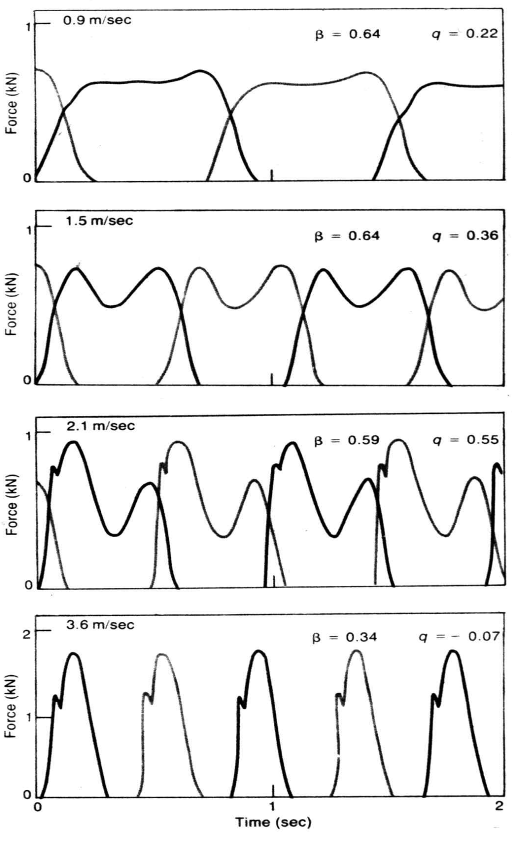
$$a ? \frac{v^2}{l} \quad \text{resp.} \quad g ? \frac{v^2}{l} \qquad \text{(eq. 1)}$$

Because the downward acceleration of the center of mass cannot exceed gravitation (see equation 1), we get the equation 2 by algebraic transformation.

$$v_{max,walk} ? \sqrt{gl} \quad ? \quad v_{max,walk} ? 2.5m/s \qquad \text{(eq. 2)}$$

Assuming a leg length of 0.9m, we get a maximum speed of about 2.5 m/s. If a person wants to move faster, it has to run to achieve higher speeds.

## 2.3 Force analysis




Graphic 5

To find out, how energy fluctuations in the body are regulated, especially to see, what happens in the legs, Alexander and Jayes recorded in an experiment in 1980 (Alexander, 1984b) the forces exerted on the ground using pressure-sensitive mats. Only the vertical forces were examined.
The four graphs in graphic 5 show forces for slow walking at 0.9 m/s in the top graph, for walking at medium speeds in the second graph and for fast walking – almost at the edge of running in the third graph. The last graph that looks like a series of half sine curves represents the forces recorded while running. Dark coloured lines represent one foot, the lighter ones the other one.
As we can see, in normal walking, the force rises rapidly after the foot is set down. At slow speeds, the curve becomes a plateau and falls in the end when the foot is lifted again. But in faster speeds, we get a two-humped curve, because forces are larger immediately after putting the foot on the ground and just before lifting it again.

While running, there's no phases with both feet on the ground. There's now a one-humped curve, that shows, that there's only a large force peak while setting a foot down. But forces are much larger while running, it's almost double values, if we have a look at the y-axis.
Alexander & Jayes (1980) characterized the curves using two factors:

? , which is a duty factor. It is that fraction of the duration of a stride during which each foot is on the ground.

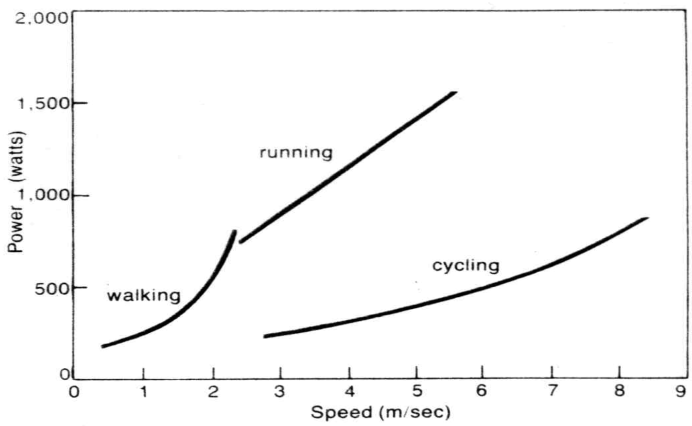
Q, which is the shape factor of the curve. If the curve was a perfectly shaped half sine curve, q would be 0. It is large and positive for two-humped curves and negative for one humped curves. They used a mathematical model, that set ? and Q in relation to the work done in walking or running. Using this model, they could express the work done as a function of ? and Q. It showed, that the curves recorded represent gaits, where least energy is used for that particular speed. (for more information see Alexander, 1984b and Alexander & Jayes, 1980)

## 2.4 Energy costs of different gaits

In tries to answer the question, if gait selection is optimized for certain speeds, there have been experiments measuring the total energy cost of organisms while running or walking. Therefore, the oxygen uptake was measured using devices like shown in graphic 6.

Graphic 6

This method has a few limitations: One limitation is, that sprinters f.e. build up an oxygen debt while running at very high speeds. This is what one calls anaerobic phases. There's also the restriction, that one cannot directly measure energy consumption of leg muscles or certain muscle groups using this method. (Alexander, 1984b) Using this method, Alexander (1984b) measured energy consumption for different forms of locomotion in an experiment. The graph in graphic 7 shows, that energy consumption rises at increasing speeds and suddenly, it's more economic to change gait. That's where both curves (walking and running) intersect. At this point, it would be more expensive to walk fast than to run slow.




Graphic 7

Also, we can see the energy consumption curve for cycling: It may give us the impression, that moving on legs is in fact not very efficient, compared to locomotion on wheels. But of course, legs have many advantages which wheels haven't.

## 2.5 Gaits in quadrupeds

In quadrupeds, there are three basic forms of gaits.

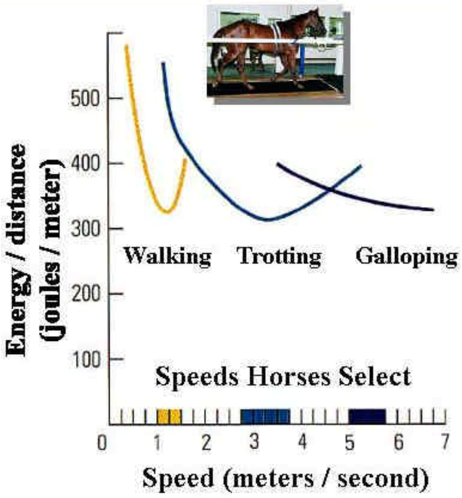
| | |
|---|---|
| Walking | is for slow speed, |
| Trotting | for medium speeds and |
| Galloping | for high speeds. |

These forms of gaits will be explained more detailed later on. There are also several subforms of the faster gaits, f.e. the canter and the pronk for galloping.
Also in quadrupeds, the principles remain the same: For a particular speed, the cheapest gait ensuring most economical locomotion is selected.

## 2.6 Economy of gaits

Now that we now, that certain speeds require certain gaits, we‘ll have a little more detailed look at that.

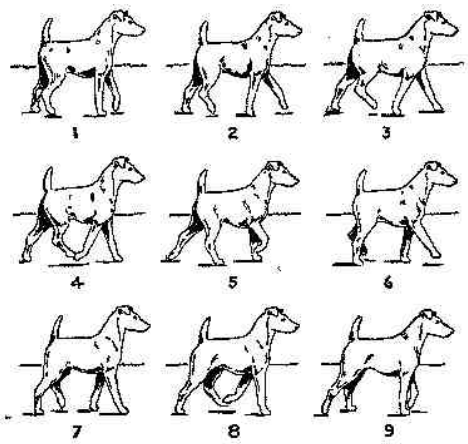
Graphic 8 shows the ratio between energy consumption and distance. (Full, 2000). We see that a horse chooses walking for speeds up to about 2 m/s. From about 2 up to about 4.5 m/s, it trots, while it starts galloping for higher speeds. So there‘s an optimal gait for every speed. But does a horse move at every speed? This experiment has shown, that horses prefer certain speeds. It‘s the ones marked yellow, light and dark blue on the x-axis. Where the u-shaped curve is lowest, the ratio between energyconsumption and performance is best. Also, particularly the speeds are preferred where this ratio is best and in-between-speeds with a suboptimal economy are avoided.




Graphic 8

## 2.7 Quadruped gaits

### 2.7.1 Walking




Graphic 9

In Nunamaker &. Blauner (1985) and also on Oricom-Technologies, (Unknown publication year), quadruped gaits at different speeds are described.

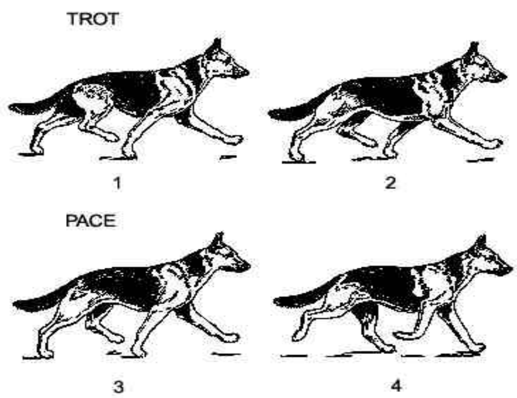
The dog in graphic 9 walks with a 4-time gait, LF (left-front), RR (right-rear), RF (right-front), LR (left-rear), then repeat. Presumably, most dogs prefer to start the walk with a front leg.

It is noticable, that balance and support are maintained by the LR+RF "diagonal" while the LF and RR legs are suspended [positions 1, 2], and by the opposite diagonal for the other 2 legs [positions 5, 6]. At the start of each step [positions 1, 5], the legs of the support diagonal are vertical, and the center of gravity of the dog is in the middle of the diagonal. Then the center of gravity shifts forward as the stepping leg is extended [positions 2, 3, 6, 7], giving forward momentum to the body.

### 2.7.2 Trotting

Positions 1 and 2 of graphic 10 show the stages of the trot gait. It is used for medium speeds and normally 2 feet are on the ground simultaneously. It could be described like 2 humans walking behind eachother. The Trot is a 2-time gait, LR+RF alternating with RR+LF.

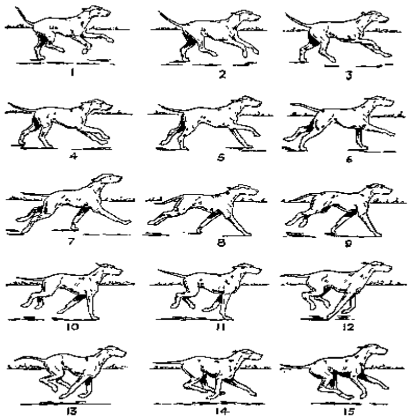
Pace (as shown in positions 3 and 4 of graphic 9) is a „fatigue“-gait and never has been highly developed in dogs. Its difference to the trot is, that the two legs in line move in the same direction (Nunamaker & Blauner, 1985; Oricom-Technologies, Unknown publication year).




Graphic 10

### 2.7.3 Galloping

Galloping is a 4-step gait, shown here on graphic 11 as Left Rear, Right Rear, Left Front, then Right Front. The leg ordering is very different from the walk and trot. The RF leg is actually the "leading" leg here. The characteristic of this gait is that the leading leg bears the weight of the body over longer periods of time that any other leg, and is more prone to fatigue and injury.



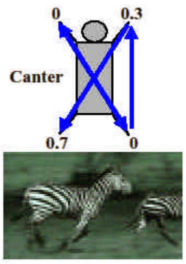
Graphic 11

The single suspension phase [positions 13-15] is initiated by catapulting the entire body off the leading leg [positions 10-12]. The force comes from the back legs pushing off onto the non-leading front leg, and then onto the leading leg [positions 3-8].

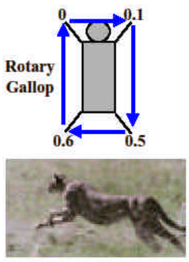
There is a position where all 4 legs are under the body, and others where either the 2 front or 2 rear legs are extended away from the body, but none where both fronts and both rears are extended simultaneously. This gives a degree of rocking to the body because the center of gravity moves forwards and backwards (Nunamaker & Blauner, 1985; Oricom-Technologies, Unknown publication year).

### 2.7.4 Further galloping forms

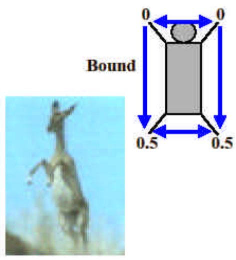
There exist several other galloping forms, which most are specific for certain groups of animals. The canter f.e. is mostly shown in hoofed animals.



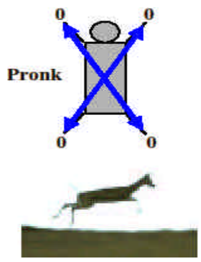

Graphic 12




Graphic 13




Graphic 14




Graphic 15

Bound (graphic 14) and pronk (graphic 15) are gait forms which can be observed in african animals, f.e. the pronghorn. (Full, 2000) The diagrams in the upper parts of graphic 11 to 14 explain the contact pattern of the animals feet on the ground. As we can see, the bound gait changes from both forelegs to both hindlegs, while the pronk is a gait, where all 4 legs contact ground simultaneously and in a next phase all are off the ground simultaneously. The canter gait and rotary gallop are special forms of galloping which can be found in certain animals.

## *2.8 Stability in rapid locomotion*

Static stability means, that the vertical projection of the center of gravity of a passively stable system always remains within the convex region formed by the contact points of the feet on the ground. This region is called the support polygon. Statically stable machines can stop moving at any time in the locomotion cycle and maintain balance. They typically have four or six legs but may be bipeds with large feet. In contrast, dynamically stable systems utilize dynamic forces and feedback to maintain control and are stable in a limit cycle that repeats once each stride. Dynamically stable machines have been built with one, two, and four legs. Because dynamically stable systems are more difficult to design and analyze, the early development of legged robots focused on statically stable machines. In real life, few animals move using static stability. Even walking in humans isn’t achieved by static stability anymore. Faster speeds therefore require dynamic stability. (Boone & Hodgins, 1998)

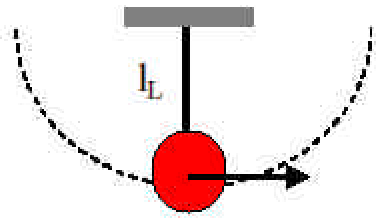
## *2.9 Gait changes among animals*

### 2.9.1 Question of comparability

We know, that gait change according to certain speeds is a basic principle in locomotion. But how can we compare different animals when they are morphologically quite different. They vary in body size, leg length, mass and other characteristics, that may be relevant for locomotion.

### 2.9.2 Froude numbers

If we have a look at what influences the speed an animal or human travels. Its time, leg length and gravity.




**Graphic 16**

Froude number is a measure for speed, that is not dependet of individual characteristics of certain morphologies. If you move in an arc, as graphic 16 shows, then your acceleration may be expressed as a function of radius and speed. (see eq. 1). From this, froude numbers are derived. The calculation of froude numbers is shown in equation 3.

$$\textbf{froude number} \ ? \ \frac{\textbf{speed}^2}{\textbf{acceleration} \ ? \ \textbf{length}} \ ? \ \frac{\textbf{v}^2_{\textbf{locomotion}}}{\textbf{g} \ ? \ \textbf{l}_{\textbf{leg}}} \qquad \text{(eq. 3)}$$

It's speed square divided by gravity times leg length. Dynamically behavior may be characterized using froude numbers: Dynamically similar behaviors have similar froude numbers. Therefore, froude number is a dimensionless speed. (Full, 2000)

### 2.9.3 Gait and froude number

If we compare for instance a dog to a camel:
Let's take 0.5m for a dogs legs and 1.5m for a camels legs. A dog starts to gallop at about 3.5 m/s, while a camel starts to gallop at 6.1 m/s.

Dog: $$\textbf{froude\#}_{2.5} \ ? \ \frac{(\textbf{3.5m/s})^2}{\textbf{9.81m/s}^2 \ ? \ \textbf{0.5m}}$$

Camel: $$\textbf{froude\#}_{2.5} \ ? \ \frac{(\textbf{6.1m/s})^2}{\textbf{9.81m/s}^2 \ ? \ \textbf{1.5m}}$$

If we calculate it, we get the same value of 2.5. Therefore, most mammals change gait at similar froude numbers. (Full, 2000)

### 2.9.4 Why do animals change gait

Finally, we conclude:Animals (and also humans) change gait to increase speed. While at slow speed, gait change is limited due to physical restrictions, at higher speeds, properties of the body and dynamical stability allows faster and dynamically stable gaits.
Primarily, energy costs per distance are reduced by using an appropriate gait, as we've seen.
Experiments also have shown, that gait change is used to decrease strain on body parts. Claire Farley from Berkeley University California (Full, 2000) has shown, that horses carrying weight change gait differently than in idle conditions.

# 3 Practical considerations and examples

## 3.1 Problems to considerate for Rapid Locomotion Systems

If we are interested in building a Rapid Locomotion System there are of course a hole bunch o issues to take into consideration. In this chapter we will shortly point out some of them.

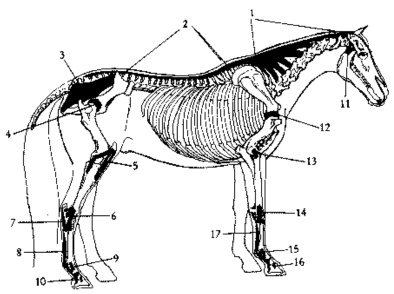
## 3.2 Speed up, slow down and stop

The goals here are in, how to accelerate, when to change gaits, how to break...
To point that you lets look on natural behavior.
Animals often don’t run with a constant speed, they change their velocity several times during their activities. You might thing of normal changes in gaits like the one we mentioned before in which horses at a certain point change from walk into trot and further on into gallop or on reactive velocity changes like the ones we know from wild cats during hunting.
We even might think of some animals that may stop instantaneously, looking around focusing on something and then move on.
But why do the animals do that? As we already saw they do it for optimizing energy consumtion. However they also do it for reorient themselves, prevent obstacles, watch out for danger and for muscle regeneration.
The hole movement from the beginning to the speed up till the breaking process seams to be a optimized way to get most out of the energy available and combining it with other attitude needed.

A Project where they paid attention on some of this goals is the Scout II Project from the McGill University in Montreal. The Project realizes variable speed Walk including acceleration
and breaking to null.

## 3.3 Balance & Stability

This goal focus on how to maintain itself balanced while being in motion, how to run and stabilize oneself at anytime. For this approach in motion we have to ways to get hands on. On the one hand we can take this issue into consideration while designing the embodiment while on the other hand we also have to worry about it during motion.
During designing for example we might use physics and take some passive dynamic walking into consideration or we might build the embodiments skeleton as stable as possible for your needs.



Graphic 17

Looking in nature for example we will find some animals like horses and dogs having often the upper leg segments angle inwards, centering the weight of the torso and giving the frame front-back stability.

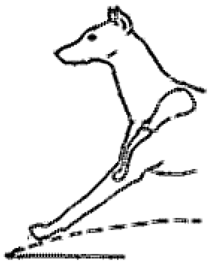
There are a lots of projects around working on this issues. You find some approaches for these for example in Sony’s Aibo or in the Running Dog Robot from Fumiya Iida at the AILab of University of Zurich. (graphic 18)

Graphic 18

### 3.4 Self sufficiency

The goal on which we want to focus know is energy consumption or how we can prevent losing to much of it. The main ideas of course to use as few as possible and when ever possible to recollect or store energy. This can be done as we heard already on optimizing the gaits changes for the various speeds. But it also can be done by reconvert used energy for example from the impact of our formal step, were we have a lot of kinetic and potential energy we could get out of the last step and release it for the next step. (see graphic 19)

This is really one of the huge problems specially in running, were most of the potential and kinetic energy is lost on Impact with the floor and transformed into heat.



**Graphic 19**

But how can we prevent losing to much Energy in running? By “simply” temporally store it, and prevent that is would be turned into heat. Remembering our physics lessons we might think of springs as a way to store the energy. Like children do it playing with a pogo stick.

Various tests in that field showed that in Nature most of that is done in Muscle and Tendon and a little also in Cartilage, Ligaments and Bone. However these works on animals going back till the 70 also showed that not all of them have the same influence in Energy storing, and that it even depends on the type of fibred muscles. Where as long-fibred muscles for example cannot be involved in energy saving, muscles with short fibers and long tendons like the one present on kangaroos can very well.

There are again a lot AI-Projects around focusing on this subject. You find some of these considerations for example in The Uniroo and The Monopod Project from the MIT LegLab

### 3.5 Conclusion

rapid locomotion combines different aspects of locomotion itself, body design and energy saving for the one goal of putting back distances in a more economical way.

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