University of Veterinary Medicine Budapest
Department of Anatomy and Histology

Diploma-Thesis

The use of connected devices for the optimization of racing performances in horses

Experimental study on different physiological and biomechanical parameters

Emma Aimonetti

Supervisor: Dr. Gerics Balázs
Assoc. professor

Budapest
2019

List of abbreviations

HR	Heart Rate
BPM	Beat Per Minute
HRV	Heart Rate Variability
ANS	Autonomic Nervous System
ATP	Adenosine Tri-Phosphate
ADP	Adenosine Di-Phosphate
RR	Respiratory Rate
VO2max	Maximal oxygen consumption
CRT	Cardiac Recovery Time
VLA4	Velocity at which blood lactate concentration was 4 mmol litre−1
H+	Hydrogen Ion
MCT	Monocarboxylate Transporter
CRH	Corticotropin-Releasing Hormone
ACTH	Adreno Corticotropic Hormone
HPA	Hypothalamic Pituitary Adrenal
OTS	Overtraining syndrome
SS	Stamina Score
O_2	Dioxygen
Ca2+	Calcium ion
K+	Potassium ion
CRT	Capillary Refill Time
PCV	Packed Cell Volume
SAA	Serum Amyloid A
CO	Cardiac Output
SV	Stroke Volume
LRC	locomotor-respiratory coupling

List of figures and tables

1 Introduction

Racehorses are amazing athletes, selected and trained to fulfil their best potential. In order to perform at their maximum capacity, their physical and mental health should be the priority of trainers, jockeys, owners, vets, farriers, and any professional around them. This goes by an accurate assessment of their physiological needs, and the establishment of a specific program adapted to their actual level of training, considering each individual separately.

Nowadays, the use of connected tools / wearable technologies is at disposition to help optimizing the fitness and health status of horses during physical training. Electronic monitor systems have been on the market for a few years, and are helping to assess the fitness of the horse by using a scientific approach. Responses of the musculoskeletal, nervous, respiratory, and cardiovascular systems to exercise are co-dependent, and physiological and biomechanical parameters are intimately correlated. Overtraining and non-adapted training ultimately lead to physical imbalance, causing muscle soreness, decreased performance and in worst case, fatal injury of the athlete.

The present study focuses on two aspects of equine performances:

a) The following three locomotor parameters, recorded by an electronic monitor device are evaluated: regularity, frequency and length of the stride.
b) The maximal heart rate reached during exercise - recorded by the same device, and the recovery time of the horse will also be studied.

We ask the following questions: Is the regularity of the stride inversely proportional to the stride length and stride frequency? Do horses exercising in the "red zone" have a longer recovery time?

Finally, we will present an example of training analysis - which can be performed with a cardiac and locomotor monitor device, in order to increase performance of the horse.

The whole study was conducted with the **Equimetre®** device, an innovative product of the ***Arioneo Company***.

2 Literature Review

2.1 Assessment of the fitness level of the horse

Basics parameters to evaluate

Assessment of the fitness level of a horse is necessary in order to optimize his training, allowing him to perform as its best level, and to avoid exhaustion and fatigue.

The athletic capacity of horses is the result of a complex combination of physiologic properties. The following physiological parameters have to be evaluated in order to assess the potential and the level of training required for a specific horse.

Heart Rate (HR): "*Cardiovascular fitness is of prime importance for the horse to efficiently utilize the other body systems*" (Freeman, 2003), and measuring the HR is a simple and reliable way to assess the physiological fitness of the horse during an exercise. It should be evaluated at rest, during and after exercise. The resting heart rate of an adult horse is 30-40bpm. Contrary to humans, the resting HR does not seem to decrease as a result of physical conditioning (Freeman, 2003). This statement has been confirmed by the Kentucky Equine Research in 2010 which stated:

> "Because the resting and maximal heart rates are not affected by changes in physical condition, they are not useful as indictors of fitness. One of the best measurements of a horse's overall condition is recovery rate, or the speed with which the heart rate returns to resting level following exercise."

In 1883, Wilson *et al*, showed that the heart rate of horses during exercise increases as a linear function, to a value between 120 and 210bpm. Beyond this intensity window, the heart rate is reaching its maximal value, called HR max, which can reach 240bpm. We could explain it by the fact that the cardiac muscles do not need to increase their contraction rate when getting closed to VO_2max, as the adenosine tri phosphate (ATP) would be produced by the anaerobic glycolytic metabolism (Valette and Wolter, 1988). The maximal HR does not change with training, but the more the horse become fit, the more he can exercise at his maximum heart rate (Geor, 2000).

During intense exercise, the heart beats around 4 times per second, and corresponds to the maximum rate at which the cardiac chambers are able to refill during contraction. Maximal heart rate in adult horse is between 220 and 260 bpm and is variable between individuals.

Heart rate Variability (HRV): Heart rate variability or HRV is the physiological phenomenon of the variation in the time interval between consecutive heartbeats in milliseconds. ECG-based methods detect the R wave in the QRS complex and calculate the time between R waves, so called R-R interval. HRV on exercising horses has not been studied a lot yet, as it can be complicated to separate premature beats from normal beat-to-beat variation at higher rates on an electrocardiograph (ECG). It is important to remember that the HR is mostly regulated by the autonomic nervous system (ANS). In 2019, Frick *et al* describes really well the physiological process at the origin of the heart rate variability:

> "Heart rate is closely regulated by the autonomic nervous system. In the horse at rest, tonic vagal inhibition decreases the HR and increases short-term HRV. At the onset of exercise, withdrawal of vagal tone increases HR to approximately 100-120 beats/min. Sympathetic tone and neuro humoral regulation further elevate the HR above 120 beats/min. As HR rises, differences between R-R intervals become less apparent. Once a horse enters the recovery phase after exercise, sympathetic tone withdraws and parasympathetic tone again predominates. This recovery phase is frequently associated with vagally mediated arrhythmias such as 1st and 2nd degree atrio-ventricular block or marked sinus arrhythmias which have been referred to as "punctuated decelerations" by some authors. In addition, premature complexes are commonly reported in horses during the recovery phase, which may also increase HRV."

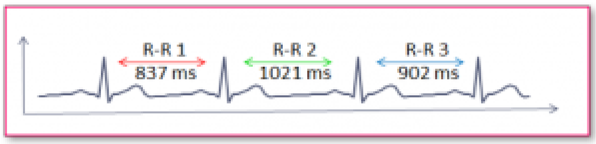


Figure 1: Calculation of the *Root Mean Square of Successive Differences (RMSSD) which represents the quadratic mean of the successive differences between several R-R intervals. (CHELS, 2019)*

Heart rate variability (HRV) is commonly used in humans as an early marker of fatigue (Cassirame, 2015), and studies are currently led on horses.

Cardiac recovery time (CRT): Once the exercise is terminated, the heart rate drops rapidly during the first 5 minutes. We call it the recovery heart rate, and it corresponds to the time for the HR to decrease to 120 bpm. Poorly performing endurance horses have higher post exercise heart rates compared with better performers. Abnormally delayed recovery heart rates should alert trainers to the possibility of illness or lameness (Cardinet *et al*., 1963).

Indeed, CRT can be used to evaluate fatigue or pain. In case of metabolic imbalance caused by dehydration or electrolyte deficiency for example, this index will be more elevated.

This is really important to be able to detect the first signs of fatigue, in order to avoid progression to exhaustion, and identify lameness to prevent permanent musculoskeletal injury (Flaminio, 1996).

Respiratory rate (RR): The RR at rest is in between 8 to 16 breaths/min. During high intensity exercise, it can reach 180 breaths/min (Firshman, 2010).

VO_2max: Maximal oxygen consumption (VO_2max) is the maximal amount of oxygen used by the athlete during maximal exercise to exhaustion. VO_2max is sometimes referred to as the *peak aerobic power*. In humans, there is a trend for the best athletes to have the highest VO_2max values. Elite human athletes have VO_2max values ranging between 69 and 85 milliliters oxygen per kilogram body weight per minute (ml O_2/kg/min), whereas Thoroughbred racehorses have VO_2max values twice as high, about 160 to 200ml (Hodgson *et al.*, 2014).

Lactate level:

In humans as well as horses, one of the most evaluated blood biochemical measurement is the blood lactate concentration. The concentration of lactate in resting horses is about 1mmol/L, and is going to increase progressively during exercise.

> ” The exercise intensity at which lactate concentrations rise more steeply is often termed the lactate threshold, which occurs at a lactate concentration of 4 mmol/L, the VLA4. Traditionally, the VLA4 has been considered to approximate the anaerobic threshold, mirroring the metabolic transition from predominantly aerobic to anaerobic energy sources, and this calculated value increases with improved fitness.” (Hodgson *et al*., 2014).

Indeed, in a less fit horse, we will observe a rise in blood lactate concentration at a lower exercise intensity than in a fit horse. It means that the lactate threshold is reached more rapidly in less fit horses than in performance horses. Lactate threshold indicates the concentration of lactate and / or lactic acid, where it begins to increase exponentially. The reason behind this process is the following: Muscle cells release lactate into the blood to be converted into glucose by the liver, by help of the Cori cycle. The high rate of ATP hydrolysis in the muscle release Hydrogen ion (H+) as they are co-transported out of the muscle into the blood via the monocarboxylate transporter (MCT). Bicarbonate stored in the blood begins also to be used up. This process happens when lactate is produced faster than it can be metabolized by the muscle, and metabolic acidosis happens. If the horse exercises at a level below the lactate threshold, any lactate produced by the muscle is removed by the body without building it up.

Hormonal events: During normal exercise, we can observe a decrease in insulin, and an increase in catecholamine (dopamine, norepinephrine, and epinephrine), cortisol and glucagon. The net result is the increased delivery of glucose due to increased glycogenolysis and gluconeogenesis. Cortisol, corticotropic-releasing hormone (CRH) and adrenocorticotropic hormone (ACTH) level can be indicators of overtraining (De Graaf-Roelfsema *et al.*, 2007).

Nowadays it is believed that the combination of different hormonal parameters appear to be good indicators of overtraining.

Environmental and internal stressors are at the origin of homeostatic imbalance, which need to be re-equilibrated during the recovery phase. If the training of the horse starts before complete recovery and adaption has not occurred yet, there is a risk of overtraining. If an imbalance between these two phases persists, *"the homeostatic disturbance won't be only expressed at the cellular level but also at a somatic (whole body) level, thereby characterizing it as a disease, called Overtraining syndrome (OTS)."* (De Graaf-Roelfsema *et al.*, 2007)

Symptoms associated with OTS include lethargy, poor appetite, weight loss, irritability and anxiety, change in heart rate at rest, exercise and recovery.

The training should introduce stress gradually, using specificity and gradual overloading, without causing injury. We distinguish 2 phases during the reestablishment of homeostasis: catabolic and anabolic phases.

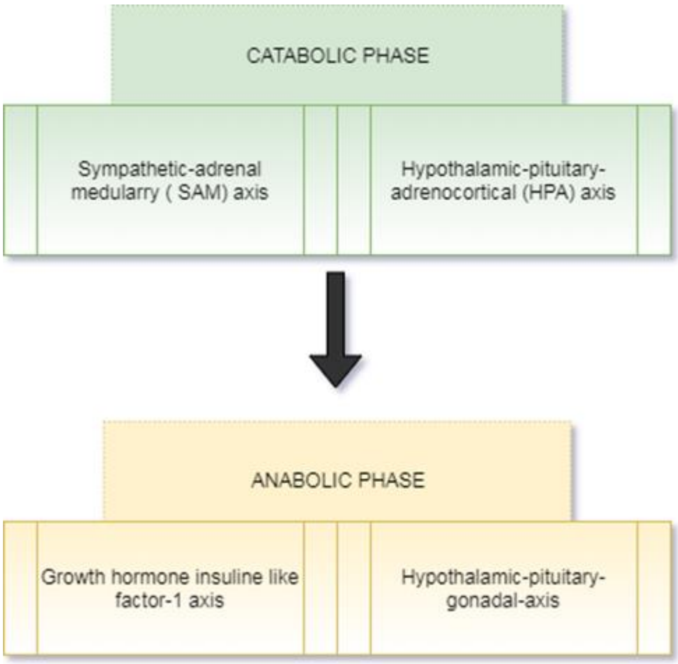


Figure 2 : The 2 Phases during reestablishment of homeostasis after introduction of a stress factor. Diagram taken from the lecture slide of Dr.Kutasi, made for her elective course Equine Sport Medicine hold in 2017.

Cortisol plays an important role during the catabolic phase, and influences the hormonal change during the anabolic phase. A good representative of the latter is the growth hormone (GH). It is hypothesized that GH increases after exercise, and provides an energy source during recovery by inducing lipolysis and synthesis of new proteins (De Graaf-Roelfsema *et al*., 2007). The stimulation of the hypothalamic pituitary adrenal axis (HPA) is induced by different types of stress (environmental, acute exercise or internal stressors) and starts with the release of cortisol, CRH and Vasopressin by the hypothalamus. CRH released from the hypothalamus controls the level of ACTH produced by the anterior pituitary gland.

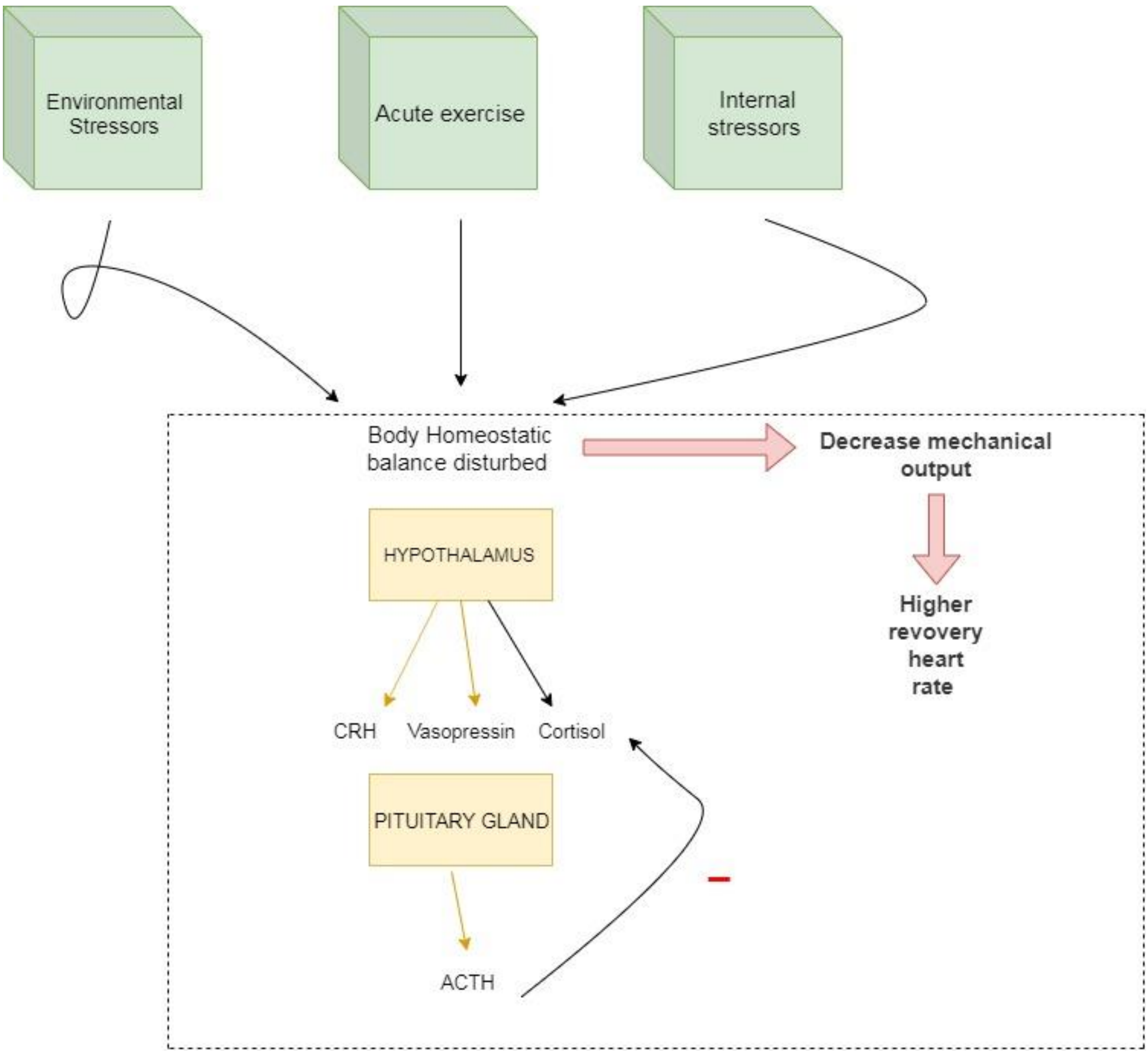


Figure 3: Overview diagram of the hormonal response to acute exercise on the muscle metabolism. Inspired by a diagram made by Dr.Kutasi for her elective course Equine Sport medicine, in 2017 and adapted by Aimonetti, 2019.

Locomotor parameters: These are certainly important factors to take into consideration when assessing the fitness level of a horse. A gallop test has been introduced in order to evaluate the locomotor profile of Thoroughbred, and the following results about stride frequency and length have been established by Hinchcliff *et al.* in 2008:

Stride frequency: The stride frequency is also called the cadence. In other words, it is the number of strides taken in a given time. It is measured in strides per minute or stride per second. Most horses will have a stride frequency of between two and two and half strides per second. It appears that, generally, sprinters will have a higher frequency than middle and long distance horses (*At the races,* website, 2018). Also, the best performers during races had a higher stride frequency, stride regularity and diagonal dissociation.

Stride length: It is the size of each stride. It corresponds to the distance between two successive hoof falls of the same leg. The average length stride of a racehorse tends to be 20 feet (6.1m). An increased stride length does not seem to be correlated with better performance, as it is directly correlated with velocity, and could result in a decrease in stride regularity. On the other hand *"horses breathing is synchronized to take one breath for every stride; therefore shorter striding horses will have to work (i.e. take more breaths) in order to keep pace with a longer-striding counterpart."* (*At the races*, website, 2018).

Combining length and frequency:

A key indicator for a top class horse, according to some research about stride data analysis, would be a combination of both long stride, and high frequency.

Indeed,

Length stride (meter) x frequency (meter/second) = speed (meter/second)

It has been demonstrated by Dusek *et al.* in 1970, that horses run with the increase of stride length and stride frequency in proportion to the running velocity. In 1993, Kai *et al.* observed that the stride frequency reaches its peak almost immediately after the beginning of the course, while stride length will reach its maximum later on. Hiraga *et al.* (1995) demonstrated the relation between stride length, stride frequency, step length and velocity at the start dash in racehorse:

"Stride frequency reached its peak immediately after the start, while stride length required about 25-30 strides to reach its maximal level. Although substantial increase in velocity was attained by an increase in stride length, it appears that acceleration during the start dash is achieved by maximal increase in stride frequency. Mid step length reached a maximum level following several strides, however airborne step length required more time to reach its maximum. Therefore acceleration during the start dash is achieved by a maximal increase in mid step length since it is not possible to quickly increase airborne step length."

To resume: during a race, a quick acceleration at the beginning and end of the race is initially characterized by a high rate of stride frequency, followed by stride lengthening in order for a horse to win.

The maximal stride frequency depends on a few biological factors: length of the limbs, weight distribution and elasticity of the limbs, without forgetting the percentage of fast-twitch muscle fibers. We call "wheel gallop" the phase when the gravity center of the horse is lowered and kept at the same height during the entire stride. A maximum energy is produced during this phase, used for propulsive work. In fact, no waste of energy is observed for vertical oscillation. Regularity of the stride is then really important, and can be unfortunately affected by the increase in speed (Hinchcliff *et al.*, 2008).

<u>Regularity of the stride</u>: Is characterized by a constant cadence, even if the stride length increases. The gait should be as fluid and free as possible. The regularity is calculated by the correlation between one stride and the next stride.

In the practical part of this study, the regularity of the stride while galloping will be studied, and correlated to the stride length and stride frequency.

<u>Motion and stride length analysis of race videos:</u> Analyzing videos by a motion analysis system is used during training in order to determine stride length and quality of motion. As the horse industry strives to bring ongoing improvements to the quality of training and performances of horses, DataTrack International® LLC introduced another parameter, called the Stamina Score. It "*gives the indication of whether the horse may be able to go longer successfully, or if he is currently running at its optimum distance.* " (DataTrack International® LLC´s website, 2019). The Stamina Score (SS) is calculated by taking different points of the track during the race, and comparing the stride length of the very same horse at these points. A score above 100 indicates that the horse finishes the race by extending his stride, and he might be able to compete at a higher racing distance as well. This same company proposes to take an ultra-sound heart scan, to generate a Cardio Score based on the size, age, and fitness of the horses. The left chamber of

the heart is scanned, during diastolic and systolic state. The stroke volume is then calculated, as well as the thickness of the heart wall. These datas are then computed with other body measurements like the horse size, age, level of fitness… Horses with a result A, B+ or B. have a greater chance to win at a mile or further, and be placed in a stakes race. Horses with C or D results are often in neither of these categories.

2.2 The musculo-skeletal system

Muscle physiology

Approximately 90% of muscles are made up of myofibers, with the rest consisting of nerves, blood vessels, and fat. Connective tissue separates individual fibers (endomysium), fascicles (perimysium), and the whole muscle (epimysium) (Hinchcliff *et al.,* 2008).

From a histological point of view, skeletal myofibers are elongated, multinucleated, and are made of myofibrils. In a longitudinal section we can observe cross-striation, where lighter I bands alternate with darker A bands. Z dense striations, also called Z disks, are found within the I bands. During muscle contraction, thin filaments slide over the thick filaments, grouping the adjacent Z disks together. Myosin and others binding myosin proteins are forming the thick filaments. The myosin head contains the ATP binding, the actin binding site, and the myofibrillar necessary for the production of energy. The thin filaments are composed in majority of tropomyosin troponin complex and filaments of actin.

A sarcomere is composed by the repeating unit between 2 sarcomeres, and are considered as the unit of muscular contraction. They consist of half the I band on each side of the A band, and contain the mitochondria.

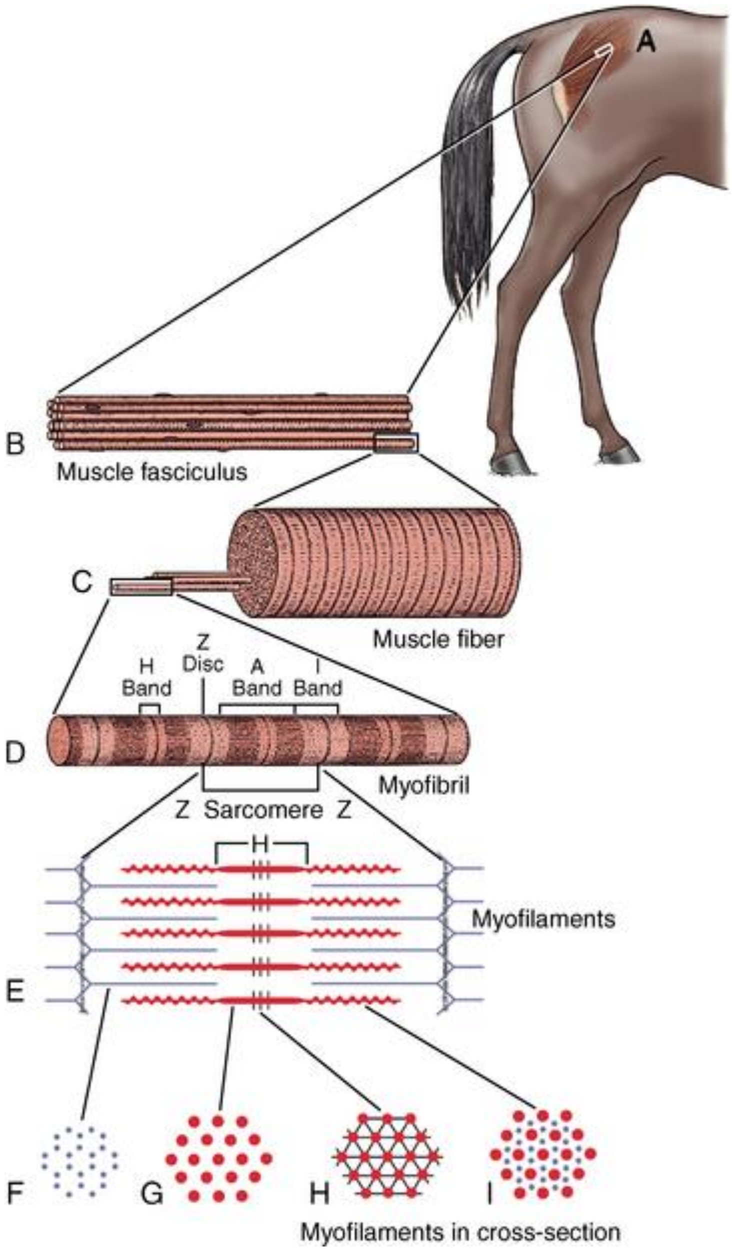


Figure 4: Skeletal muscle. The organization of skeletal muscle contractile proteins from the gross to the molecular level, online source < https://veteriankey.com/muscle-anatomy-physiology-and-adaptations-to-exercise-and-training/ > consulted the 06/10/2019

One motor unit is composed of an alpha-motor neuron, innervating a skeletal muscle fiber. Large-diameter α-motor neurons innervate fast-twitch fibers, whereas smaller ones tend to innervate slow-twitch fibers (Hinchcliff *et al.*, 2008).

The contractile force for a particular muscle is partly regulated by the rapidity of neuron discharge. We distinguish two types of fibers, type I and type II.

	Type I	Type II
Appearance	Red fibers	White fibers
Mass/Diameter per motor unit	Small	Large
Twitch velocity	Slow twitch	Fast twitch
ATPase activity	↓	↑
Glycogen reserves	↓	↑
[Mitochondria]	↑	↓
[Myoglobin]	↑ (red)	↓ (white)
Predominant metabolism	Oxidative phosphorylation	Anaerobic glycolysis
Training that ↑% of this fiber	Endurance training	Weight/resistance training
Examples of muscles	Postural muscles	Leg muscles of a sprinter

Figure 5: comparison table of type 1 and type II fibers, online source https://www.reddit.com/r/step1/comments/a2ep89/a_table_comparison_of_skeletal_muscle_subtypes/ consulted the 03/09/2019

In order to acquire the best fitness level, maximal muscular development and improved overall body tone should be one of the objectives. In racehorses, a high percentage of fast twitch muscle fibers are required.

Energy supply during exercise

It is important to remember the chemical reaction producing energy:

ATP + H2O → ADP + Pi (phosphate) + H+ + energy

Four physiologic pathways are at the origin of the energy production, needed by the muscle:

a) OXYDATIVE PHOSPHORYLATION

b) AEROBIC GLYCOLYSIS

c) FATTY ACID UTILISATION

d) ANAEROBIC PHOSPHORYLATION

During oxidative or aerobic phosphorylation, the production of ATP via aerobic pathways occurs within the inner membrane of mitochondria in a series of single oxidation reactions known as the electron transport or respiratory chain.

The availability of O_2 to the exercising muscle is the rate limiting factor for oxidative phosphorylation. Oxygen becomes immediately available to the muscle at the onset of exercise, either from myoglobin within the muscle, or from hemoglobin within the circulatory system. Oxygen in its initial quantity is sufficient for a few seconds of exercise only. Therefore, the delivery of O_2 to the exercising muscles via the cardiorespiratory system is crucial for the energy production by aerobic means.

The blood flow to muscles in exercising horses, when O_2 consumption is at a maximum (VO_2max 134 ± 2 ml/min/kg) has been estimated at 226 l/min, which represents approximately 78% of maximal cardiac output. (Hinchcliff *et al.*, 2008). Metabolites and oxygen reach skeletal muscle fibers via the respiratory, digestive and cardiovascular systems. In turn, muscle fibers produce energy in the form of ATP, which, via the contractile machinery, is converted into mechanical work. The structural arrangement of the musculoskeletal system will contribute either to moving the horse's limbs in a characteristic rhythmic pattern for each gait, or enabling diaphragm contraction, which contributes substantially to the inspiratory effort.

There are 2 main energy sources: During the first 1-2 seconds, ATP already stored in the muscle fibers is used. After 10 seconds of intensive exercise, the energy sources are ATP, creatine-phosphate, and anaerobe breakdown of muscle glycogen (Kutasi, 2017).
It means that very short exercise bouts for a few seconds usually rely on ATP as an energy source, whereas maximal exercise bouts of about 10 seconds mainly rely on ATP and creatine phosphate breakdown - besides the anaerobic breakdown of muscle glycogen. During maximal exercise bouts of longer duration (for example 20-60 seconds) the energy for muscle contraction is derived predominantly from anaerobic breakdown of muscle glycogen, and can lead to lactate accumulation.

The intramuscular elevated lactate-concentration will inexorably lead to a fall of pH in these active muscles. Muscle fatigue happens, when the intracellular H^+-level increases excessively, thus inducing acidosis. This leads to the failure of the sarcoplasmic reticulum to release Ca^{2+}, and consequently an inhibition to form actine-myosine bonds. Thereby, *"muscles with an increased buffering capacity are more resistant to changes in pH and thus have a greater capacity to continue contracting during high-intensity exercise*" (Hodgson *et al.*, 2014).

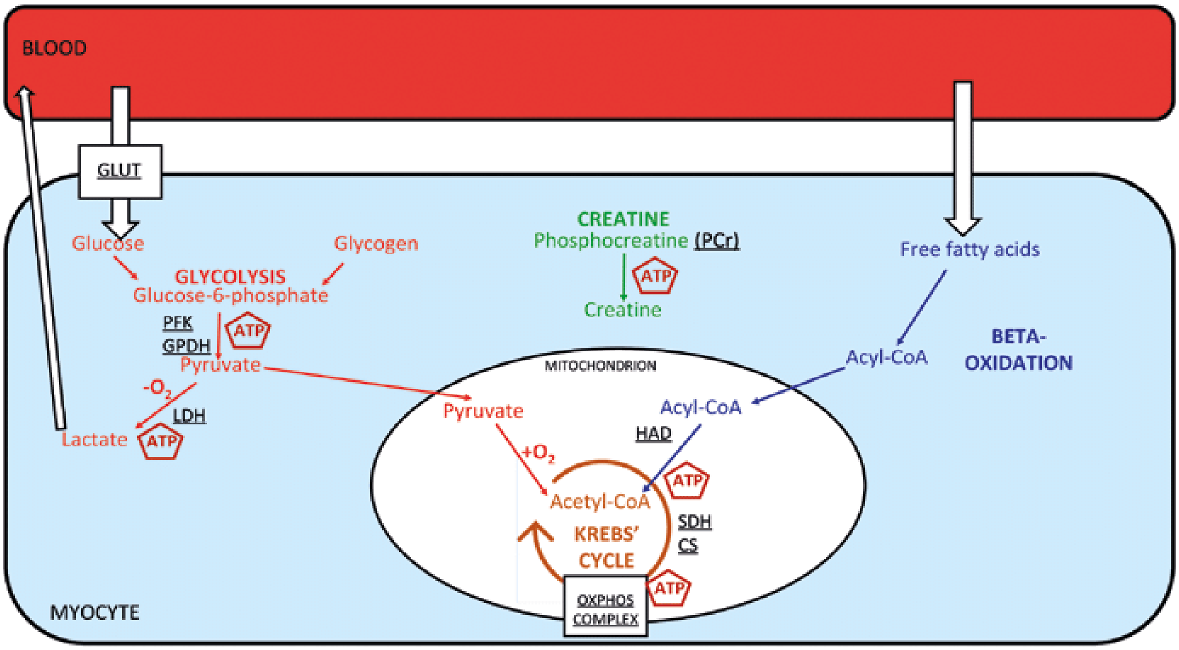


Figure 6: Fuel source and energetic pathway in the myocyte (Vermeulen *et al*., 2017)

Indeed, during an acidosis event, we observe a decrease in Ca-ATPase, phosphofructokinase and phosphorylase activity, resulting in decreased glycolysis and glycogenolysis. The intercellular K^+ level increases by diffusion through the cell membrane, as well as the sarcolemma depolarization decreases - leading to decreased muscle contraction. The consequences of this acidic environment can start with muscle fiber swelling, followed by pain sensation and acute muscle soreness.

The overall acid-base balance metabolism is dependent on the integrated response of the muscular, respiratory, vascular, hepatic, cutaneous and renal systems.

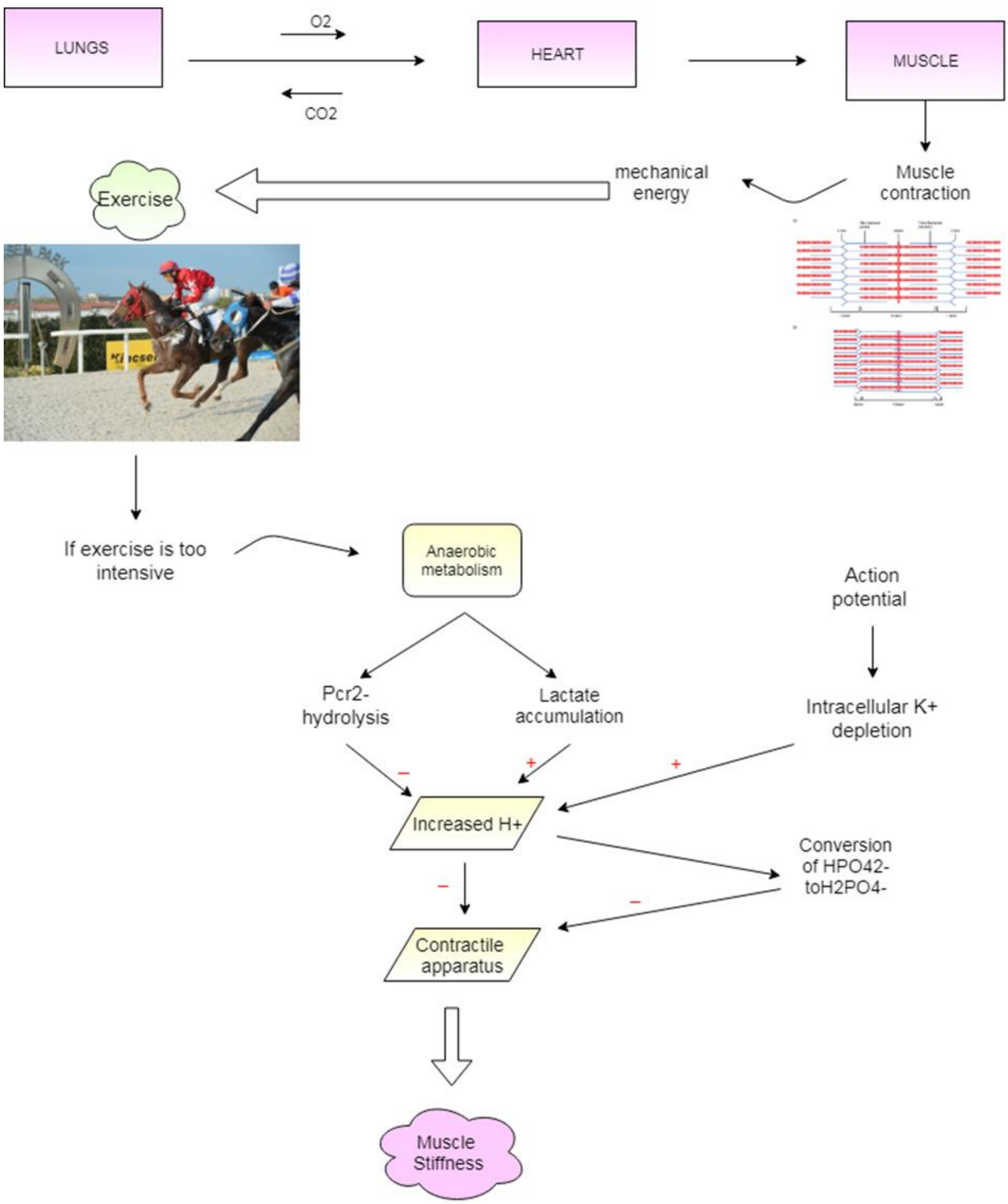


Figure 7: Overview of muscle physiology at the level of the whole organism, Emma Aimonetti, 2019.

Definition of muscle stiffness

The musculoskeletal system is composed of muscle groups and respond to internal and external factors, like nutrition, hormones, conditioning and training programs. In order to optimize power and efficiency, each muscle group should function optimally. In case of pathologic muscle tension timing and strength are affected, and the whole system decreases in efficiency:

> "The system that ideally works in perfect concert now function poorly, inefficiently, and experience regional overload, fatigue, and loss of power that decreases speed. When the muscles fail to work synergistically, the load on individuals parts increase substantially. This perpetuates the cycle of further diminished function and additionally loss of strength, efficiency and power." (Lyons, 2008)

Muscle stiffness and soreness can vary from simple muscle aches to severe muscular diseases (myopathies). These are either present from birth and are considered as genetic disorders, or develop during adulthood (acquired disorders). This following list of the different myopathies has been taken from XSL vet fact sheet on the following website: < https://www.xlvets.co.uk/sites/default/files/factsheet-files/XLVets-Equine-Rebranded-113-Atypical-Myopathy-Factsheet.pdf>

GENETIC DISORDERS:

- **Recurrent Exertional Rhabdomyolysis (RER)**

Symptoms: muscle cramps, reluctance to move, sweating and pain in affected muscle.
Diagnosis: blood sample will reveal an increase in muscle enzyme levels.
Treatment: Minimize stress, the majority of calories should be supplied as fats, not carbohydrates. Regular exercise should be kept in the routine.

- **Polysaccharide storage myopathy (PSSM**)

It is characterized by the accumulation of an abnormal form of sugar (amylase-resistant polysaccharide), as well as the normal form (glycogen) in muscle tissue.
Symptoms: Repeated episodes of tying up, often with minimal exercise. Stiffness, pain, sweating, reluctance to move, muscle wasting, poor performance, weakness and back pain.
Diagnosis: microscopic evaluation of a muscle biopsy, or genetic testing.
Treatment: After an acute episode of tying up, exercise has to be re-introduced gradually.

A strict diet is really important, with a caloric balance, a good selection of forage and fat source, and low fat / high starch concentrate should be fed.

- **Glycogen enzyme deficiency (GBED)**

Mainly found in quarter horses and paints.

Symptoms: abortion, stillborn, or sudden death.

Diagnosis: muscle biopsy and blood test to identify carriers.

Treatment: There is no treatment for GBED. Early recognition and euthanasia are preconized.

- **Hyperkalemic periodic paralysis (HYPP)**

Caused by disorders in movements of potassium in and out of muscle cells.

Quarter horses, Paints and Appaloosas can be affected.

Symptoms: facial muscle spasms, drooling, sweating, trembling of shoulders, neck and flank muscles. Inability to lift the head and lying down.

Sudden death can occur really rapidly.

Diagnostic: Genetic testing of hair or blood sample.

Treatment: Diet low in potassium, light regular exercise.

ACQUIRED DISORDERS

- **Fibrotic myopathy**

Symptoms: non painful mechanical hind limb lameness, caused by tearing of thigh muscles during intense exercise, intramuscular injection or birth trauma.

Diagnosis: Scar tissue in the hamstring muscles will lead to gait abnormality, generally characterized by a “slapping” hind limb.

Treatment: Surgery is usually recommended: tenotomy of the semi-tendinosus muscle. It can be performed under general anesthesia, or under standing sedation. Laser surgery is under development, and would be a great alternative.

- **Post anesthetic myopathy**

During anesthesia and recumbency, blood vessels supplying the muscles can be compressed, and their function altered.

Symptoms: swollen and painful muscles.

Prevention: corrected placement on a well-padded operating table.

Treatment: Intravenous fluid therapy, pain relief and intensive nursing care until the horse is able to stand by himself.

- **Atypical myopathy**

Highly fatal disease in grazing horses, caused by ingestion of sycamore seeds causing severe muscle damage, affecting the leg, cardiac and respiratory muscles.

Symptoms: Colic signs can be present, and also brown urine.

Treatment: Intravenous fluid therapy including glucose supplementation, pain killers, vitamin B,E, and selenium.

DIAGNOSTIC TEST FOR BOTH GENETIC AND AQUIRED DISORDERS

Blood test: muscle enzymes CK, AST and LDH. Can also be measured before and after exercise.

Urinalysis: muscle breakdown product, as myoglobin.

Muscle biopsy – Percutaneous needle muscle biopsy is relatively safe and atraumatic. It provides specimens satisfactory for histochemical, biochemical, ultrastructural, and molecular studies

Muscular lesions can also be caused by over and non-adapted training, particularly a too short pre-warming phase, or when the exercise is too intense.

A disproportion between the solicitation and the resistance of the locomotor apparatus can have consequences, such as muscle rupture, breakdown, muscle contracture, myopathies, and muscle fatigue. A simple immobilization of a few weeks can engender muscle atrophy.

Myositis should be considered, when the stride becomes very short, when heart rate, recovery cardiac time and muscle tone are increased. It can be followed by a profuse sweating and myoglobinuria.

It is important to evaluate the hydration level of horses after training, as hypokalemia due to dehydration can lead to muscle vasoconstriction and consequent decrease in perfusion and oxygenation of the muscles, predisposing to Monday Morning Disease. Sometimes, when alkalemia occurs along with vagal nerve stimulation, they lead to an increased HR and a risk of ileus. Hypo magnesia is also a cause of neuromuscular irritability.

Common procedures are performed when a horse is presented on an emergency basis for lameness or gait abnormality. The usual full clinical examination should be performed, including HR, mucous membrane color and moistness, capillary refill time (CRT), jugular refill time, RR, rectal temperature, intestinal borborygmy and digital pulse. Laboratory evaluation should also be performed and evaluation of Pack Cell Volume (PCV), total platelet count, leukocyte count, fibrinogen, Serum Amyloid A (SAA) and creatinine concentrations should be done (Southwood and Wilkins, 2014).

The source of lameness or gait abnormality should be identified, and the following parameters should be evaluated: stance abnormalities, gait alteration at a walk and/or degree of lameness, asymmetry between left and right limbs, swelling (synovial effusion, edema, or cellulitis), crepitus, muscle firmness, palpably increased or bounding digital pulses and areas painful to palpation or manipulation.

A septic synovial structure will be associated with heat and pain on palpation, moderate to severe lameness, synovial effusion and edema. A bone fracture will be characterized by non-weight bearing, swelling, crepitus and pain on palpation. Horses affected with laminitis stand frequently with their forelimbs forward, and shift weight from one side to the other (Southwood and Wilkins, 2014).

We can evaluate the muscular impairment by grading it, from I to III: (Jarvinen *et al*., 2013)

Grade I, mild: strain/contusion representing a tear of only a few muscle fibers with minor swelling and discomfort accompanied by no or minimal loss of strength or restriction of movement.

Grade II, moderate: strain/contusion with a greater degree of damage of the muscle with a clear loss of function (ability to contract).

Grade III, severe: a tear extending across the entire cross section of the muscle and, thus, resulting in a complete loss of muscle function.

An early detection, and the set-up of an appropriate treatment and rehabilitation plan is necessary.

It is important to consider the different physical impairments which could lead to an increase in the overall stiffness of the horse.

Musculoskeletal pain	• Muscular weakness • Decreased muscular endurance • Limited range of motion • Joint hypermobility • Faulty posture • Muscle length/strength imbalances
Neuromuscular pain	• Impaired balance or postural control • Incoordination • Abnormal tone • Ineffective/inefficient functional movement strategy
Cardiovascular/Pulmonary	• Decreased aerobic capacity • Impaired circulation
Post-surgery/injury/ return to sport too quick	

Figure 8: Physical impairment leading to muscle stiffness, inspired by Sharon Classen´s lecture *Introduction to Therapeutic Exercise*, hold in 2018 at an ISELP congress in Lexington, Kentucky

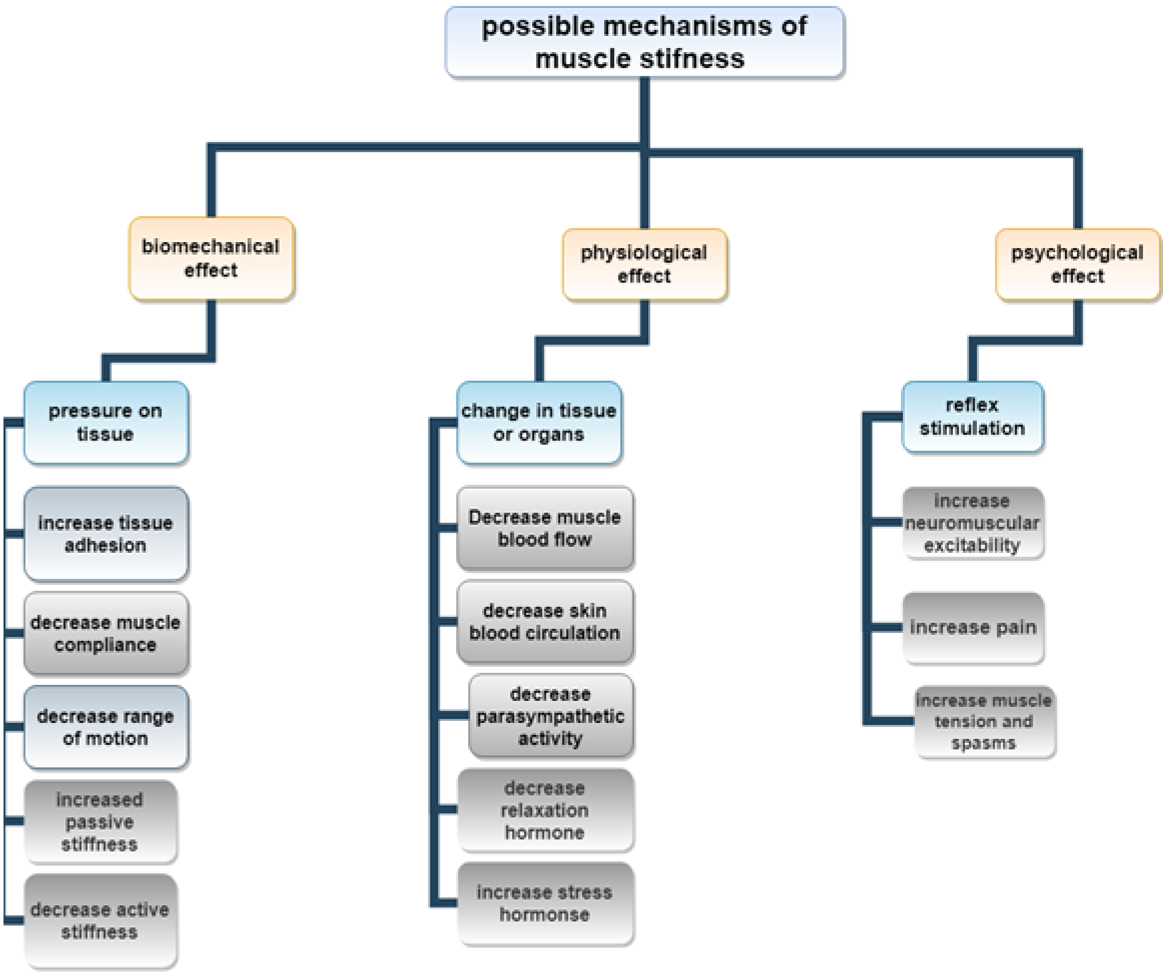


Figure 9: possible mechanisms of muscle stiffness, modified by Emma Aimonetti (Weerapong *et al*., 2005)

Dr. Sheila Lyons, published about the risk of switching horses from dirt to a synthetic surface for training and racing. She showed that these horses were presenting a clear and typical pattern of abnormal muscle tension and dysfunction on testing. She also pointed out that horses without history of traumatic arthritis could develop it if their musculoskeletal issues are not taken care of. She is enhancing the importance of a full musculo-skeletal examination, in order to protect these animal from fatal injuries, and optimize racing performances.

She gives us a baseline for musculoskeletal examination method, of sound horses and in training:

Every muscle accessible should be assessed by palpation, abnormal tension (hypotensive, hypertensive, focal or generalized spasms, tension bands within muscles, irregular temperature pattern.) and development status should be looked for. We should keep in mind that that an increased tension in a large muscle can be due to overcompensation of another physical or biomechanical problem. Then, the motor-nerve response should be assessed by the use of neuromuscular stimulation (NMS), procedure which can be realized with the help of NMS device. The next examinations are the following:

> “Neurologic reflex responses, range of motion in all planes, stretching range and quality, standard gait evaluation in hand and under tack, posture, ability to maintain square stance, static and dynamic biomechanics; and general development and musculoskeletal symmetry. These findings are recorded, on standardized forms that facilitate the comparison to identify change, whether it reflects physical and athletic improvement or identifies the development of subclinical abnormality. “(Lyons, 2008)

2.3 Relation between Cardiac output, Recovery heart rate time and Muscle stiffness

From a physiological point of view

Physiological response to exercise is a complex event that requires various different body systems in order to maintain ATP turnover. It starts by an increasing blood flow and 0_2-delivery to the muscles, while thermal homeostasis is also maintained. Muscles are also supplied, thanks to the mobilisation of reserves in the liver and adipose tissue. Hormones are regulating the process, by being in the circulation after an acute stress, as it was seen page 9 of this thesis. Catecholamines are stimulating the cardiovascular and respiratory system, and induce splenic contraction. This later one will increase the number of circulating red blood cells by as much as 50% during acute exercise. In addition, the oxygen consumption can show a 50-

fold increase, as compared to the value at rest. It is done by means of an increased pulmonary blood flow and ventilation. *"During high intensity exercise, respiratory rate increases 10-fold, and the tidal volume 3-fold, consequently the minute ventilation may reach 1.500 l/min with peak expiratory airflow as high as 90l/s."* (Hinchcliff *et all*, 2014). Cardiac output can increase up to 10-folds. Vasodilatation of the muscular vascular bed will contribute to increase perfusion and receive around 80% of the total cardiac output. Heat loss is also assured by an increase blood flow to the skin.

The cardiovascular system has an important role in setting the aerobic capacity, VO_2-max. Indeed, the energetic capability of skeletal muscles is really high, and the respiratory and cardiovascular system often can't keep up with it, as the mitochondrial oxidative enzyme capacity for utilising O_2 exceeds the capacity of the cardiorespiratory system to deliver O_2. Evidences have been shown that an increased delivery in O_2 to the muscles will elevate VO_2-max (Hinchcliff *et al.*, 2014).

It is interesting to calculate the rate of oxygen consumption. It is a product of the cardiac output (CO) multiplied by the difference in the oxygen content between arterial and venous blood. Furthermore, *"The difference in the (high) oxygen content of arterial blood traveling to the muscles and the (much lower) oxygen content of venous blood returning to the heart, having delivered much of its oxygen to the active muscles, is known as the arteriovenous O_2-difference $[(a\text{-}v)DO_2]$."* (Hodgson *et al*., 2014).

Therefore,

$$\mathbf{VO_2 = CO \times [(a\text{-}v)\ DO_2]}$$

CO is the volume of blood pumped by the heart each minute. It is the product of HR and stroke volume (SV), which is the amount of blood ejected from the heart with each contraction. Stroke volume in the resting horse is approximately 800 to 1000 ml/beat, increasing to around 1.700 ml/beat during exercise in champion horses.

$$\mathbf{CO = HR \times SV}$$

Consequently, by definition, the cardiac output will increase during exercise, as the heart rate and the stroke volume do too.

The resting cardiac output in standard horses is approximately 25 l/min. A performant elite horse is able to reach cardiac outputs in the range of 250 to 355 l/min (Davie, 2012). The stroke volume (including pre-load, afterload and contractibility) will have an influence on the cardiac performance at a submaximal level.

> "Pre-load is the end diastolic pressure which is the result of the heart chamber being stretched with increased venous return. An increased pre-load results in an increased end diastolic volume and increased stroke volume (Frank-Starling Law). In contrast an increased after-load (pressure overload) increases the resistance to blood leaving the heart, resulting in a decreased stroke volume." (Davie, 2012).

Stroke volume will increase at the beginning of exercise. This capacity - to be increased with training - will determine the cardiovascular performance of the horse. It is interesting to observe than even if the HR rises quickly to six folds of its resting value, it is not associated to a fall in stroke volume. This later one is kept at an acceptable lever thanks to the splenic contraction and increased myocardial contractibility and venous return (Evans, 1995).

On the other hand, the blood´s oxygen content is also an important parameter, and is dependent on the concentration of circulating red blood cells and their haemoglobin content. This is why it is important to assess any respiratory disorder, which could interfere with a good perfusion/oxygenation of the muscles. This is possible by measuring the arterial blood gas tensions. Hypoxemia and hypercapnia can be a response to high intensity exercise, and the severity can increase with training (Bayly *et al*., 1983; 1987). During strenuous exercise, blood primarily supplies muscles of the extremities, diaphragm and the adrenal gland, while perfusion of digestive organs and kidneys is reduced. Additional red blood cells stored in the spleen are utilized to increase the number of circulated, oxygenated red blood cells.

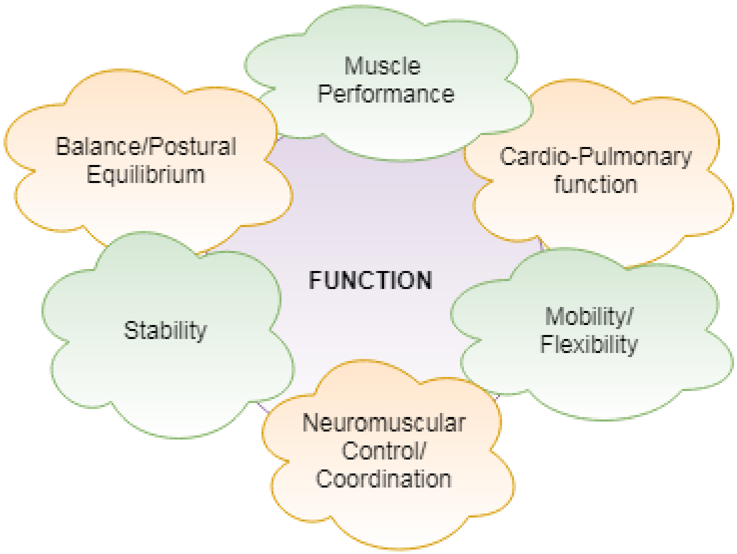


Figure 10: Interrelated aspects of physical functions, by Emma Aimonetti, inspired by Sharon Classen´s lecture "Introduction to Therapeutic Exercise", hold in 2018 at an ISELP congress in Lexington, Kentucky

2.4 Overtraining in race horses

As mentioned in the previous chapter of this thesis about hormonal changes during training, overtraining syndrome is a significant cause of poor athletic performance in both human and equine athletes.

> "In humans, overtraining syndrome is defined as an imbalance between training and recovery manifesting as a syndrome of chronic fatigue and poor performance, usually accompanied by physiological and psychological changes." (McGowan, 2008).

This phenomenon has been studied and published a lot in humans, for example by Kuipers and Keizers in 1988, and Fry *et al.* in 2006.

Physiological symptoms	**Psychological symptoms**
• Decreased performance • Prolonged recovery • Decreased muscular strength • Decreased maximum work capacity • Loss of coordination • Decreased efficiency/amplitude of movements • Reappearance of mistakes/technical faults • Chronic fatigue, amenorrhea , headaches, Nausea • Increased aches and pains, muscle tenderness • Inappetence, gastro intestinal disturbances	• Feelings of depression • General apathy • Decreased self-esteem • Emotional instability • Difficulty to concentrate during work/Training • Fear of competition • Insomnia • Irritability
Cardiovascular and respiratory	**Biochemical, metabolic and neuroendocrine**
• Abnormal T-wave pattern on ECG • Changes in blood pressure • Increased frequency of respiration • Changes in HR at rest, exercise and recovery • Increased between lying and standing HR • Increased 02 consumption at submaximal workload	• Shift of the lactate curve towards the x-axis • Decreased body fat • Negative nitrogen balance • Decreased muscle glycogen concentration • Hypothalamic dysfunction • Flat glucose tolerance curves • Decreased body weight • Decreased bone mineral content and mineral depletion • Increased urea concentration end increased uric acid production • Elevated cortisol concentrations • Low free testosterone • Decreased excretion of catecholamine
Hematological and immunological	
• Low plasma glutamine • Increased susceptibility to illness/allergy and cold • Decreased functional activity of neutrophils • Decreased total lymphocytes counts • Increased blood eosinophil count • Decreased hemoglobin, serum iron concentration and ferritin • Increased serum hormone-binding globulin	

Figure 11: Major signs and symptoms of overtraining in humans, (Mc.Gowan 2008)

Overtraining in race horses have been described for the first time by Persson in 1967. (We will refer to this as study n° 1, for better understanding.) He concluded after a study on Swedish Standardbred trotters, that overtraining syndrome in horses is correlated with the degree of red cell hypervolemia. "Overtrained polycythemic horses had reduced speed at a heart rate of 150 beats per minute (V150)." (Persson, 1967). In another study, conducted in 1999 Persson and colleagues also reported a case of overtraining:

> "A lower plasma cortisol concentrations and a decreased response by the adrenal cortex to adrenocorticotrophic hormone (ACTH) was observed. Horses diagnosed with red blood cell hypervolaemia had lower earnings and increased race times in the year of diagnosis compared with their previous performance, although, interestingly, many had been superior athletes prior to diagnosis." (McGowan, 2013).

A really interesting study had been conducted by Bruin and colleagues in 1994 (study n°2) on a group of seven horses, during when they tried to bring them into a state of overtraining. It is important to differentiate between overreaching and overtraining. Overreaching is stated to be a short-term decline in performance, which can be recovered in several days. However, in case of overtraining, recovering can take months. In this study, the horses have been trained for 187 days with an increasing training load. Then the intensity of training has been further increased to day 261. From day 270 none of the horses from the study could finish their training sessions and signs of the overtraining syndrome was registered. They had a 3-day break, then they were re-tested for signs of the overtraining syndrome - but turned out to be fine.

The study concluded that in order to talk about overtraining syndrome, the decreased performance should perpetuate even after a short period of reduce workload. In addition they concluded that as long as exhaustive work is alternated with lighter sessions, overtraining can be avoided, only overreaching would potentially be reached.

In 2002, Hamlin *et al.* (study n°3) and in 1996, Tylor *et al.* (study n°4) successfully induced overtraining syndrome during standardized exercise, and horses demonstrated a dramatic reduction in performance, to which several physiological, endocrine and behavioral signs were added.

The following table summarize the physiological signs of overtraining syndrome in horses, according to these 2 later studies.

Body weight (BW) and feed intake (Fi)

- Body weight decreases in study n°3 and n°4
- Fi decreases in study n°3 but stays constant in n°4

Haematological findings

- Association between red cell hypervolemia and overtraining syndrome in study n°1, but not observed in the 3 other studies.
- Study n°3: reduction in measured RBCs and PCV
- Study n°4: reduction in PCV but no change in RBCs volume.

Metabolic response to exercise

- Study n°3 and n°4: significant decrease in velocity at a heart rate of 200 bpm (V200) in overtrained horses, as compared with control horses.
- Study n°3: increased submaximal and maximal lactate concentrations in the overtrained Standardbreds.

Endocrine changes

- Early cross-sectional studies reported reduced cortisol response to ACTH administration in overtrained and poor performance racehorses, especially those horses with red cell hypervolaemia (Persson, 1980), but this was not confirmed in 1999 by Golland *et al*.

Behavioral signs

- Study n°2 and n°4: irritability and unwillingness from the horses to complete training: refusal to get on or off the treadmill, tossing the head while exercising, barging, pushing very hard against the front or back straps of the treadmill and sudden stopping when galloping on the treadmill without warning.

Figure 12: physiological and behavioral signs of OTS in horses, according to the studies 1 to 4.

To conclude, overtraining can be induced in horses by gradually increasing the training load. Signs that trainers should watch for are the inability to complete the intensive training, with associated, increased irritability and reluctance to exercise.

Blood chemical parameters during overtraining are not well defined yet, and can be variable. It is important to underline that muscle damage can also happen in horses, which are not overtrained. As McGowan cited in his article in 2013, around 6% of racing Thoroughbreds experienced recurrent episodes of rhabdomyolysis, and we can also observe in this case an elevated AST level. That is why in order to formulate a diagnosis of overtraining syndrome, we can't rely only on this single parameter.

2.5 Training basic principle, initial conditioning

The equine athlete undergoes constant pressure and significant musculo-skeletal changes during conditioning and competition, in order to attain maximum athletic aptitude. Consequent losses occur every year due to injuries or even death of the animals, and the race industry is constantly in need to improve itself and the well-being of its athletes. *"A sound conditioning program is often the way to prevent exercise intolerance, when no metabolic or musculoskeletal abnormality exist."* (Flaminio, 1996). Field and laboratory based principles are applied and trainers alike owners should work on the body condition of their equine athletes, to delay fatigue and influence thermal regulation.

First of all, genetics play an important role, as the relative percentage of muscle fiber type varies somewhat between breeds. The age of the horse should also be taken into consideration, as younger animals have less blood volume and weaker oxygen-carrying capacity. Also, pressure and stress on the skeletal system during excessively early and intense training could lead to concussion and lameness, as the horse skeleton reaches its full maturity only around 4 years of age or older. We need to maintain skeletal integrity and promote muscular contraction and oxygenation in order to achieve the best level of fitness reachable for a given horse.

Cardiovascular and musculoskeletal conditioning can't be effective without applying the overload principle.

> "The overload principle is the basis for all conditioning responses. This means that the system must be overloaded in some manner (intensity, speed, time) in order to elicit a training response." (Sigler, 2012).

The workload needs also to be increased gradually and progressively, in order to observe any improvement in fitness. If the overload of the system is too quick and too aggressive, breakdowns and injuries will happen. One way to assess it is the use of heart rate monitors, which can ascertain cardiovascular response to exercise.

Activity	**HR (beats/min)**
At rest	36-40
Walking	60-80
Slow trotting	80-90
Fast trotting (300m/min)	130-140
Slow cantering	100-120
Galloping (500m/min)	180-200
Galloping (800-1000m/min)	200-220

Figure 13: Estimated Heart Rates at Different Exercise Intensities (Sigler, 2012)

The other important principle of conditioning is specificity of exercise.
This simply means that:

“The horse needs to be conditioned for the type of athletic activity it will be performing later on. Most performance horses have to go through months of psychological training in order to get them ready for competition. “(Sigler, 2012).

Conditioning programs usually start at an early age and should be progressive. An effective and adapted training will start to stress the horse’s energy system, and with inclusion of good recovery bouts between sessions, the horse will get stronger and better. As we just said, this overload has to be introduced gradually, with a correct increase in intensity and frequency. It usually starts with lower speed, and long distance exercise, meaning aerobic exercise. The aim of this type of exercise is to improve the effectivity of the horse’s heart, lung and muscular functions. We want to improve the circulatory and respiratory systems, in order to be more efficient in delivering oxygen. The skeletal muscles should be more efficient at extracting oxygen from the blood. The horse´ heart rate will almost always be under 150bpm, and this program lasts around 30 days.
The trainer should use this period of training to increase the horse’s joint and tendon mobility and set a proper background for the rest of the horse’s training life. (Gibbs *et al*., 1995).

When pre-ride factors, such as elevated resting heart rate, stiffness and muscle soreness are detected, exercise should be approached with moderation, and a longer recovery heart rate should be expected. These signs should also be detected during the warm up ride, and the jockey should inform the trainer about his impressions during the ride. The aim of the warm up is to progressively start working the muscles and tendons of the horse, and accommodating further work by setting the premises of better contraction and relaxation of the muscles.

Then comes the second training phase, when anaerobic work is introduced, characterized by short but intense exercises. The overworking muscles start consuming glycogen by means of glycolysis. This phase starts when the heart rate reaches approximately 150bpm (the exact point varies between 120 and 180bpm). If the HR goes over this threshold, fatigue and overtraining are more prone to appear. These speed work should only happen one to two times per week during the first 4 weeks of this second training phase. After this, the types of training need to be alternated.

” The horse will be put on an interval training schedule, which involves a combination of distance work, and speed work, which will continue to build aerobic capacity and also build strength and speed.” (Sigler, 2012)

It is also really important to take into account the individuality of each horse. Training should be adapted to the specific needs and abilities of each horse. For example, if we decide to use the heart rate as an indicator while monitoring training activity (Craig and Nunan, 1998), we need to know the maximum heart rate of each horse, in order to know which value we have to reach, if we decide to exercise our horse to a certain percentage of his maximum heart rate. Training factors are important, and can be defined by the following question:

- < How often the horse trains > it corresponds to the training frequency.
- < How long the horse trains > it corresponds to the training volume.
- < How hard/ easy the horse trains > it corresponds to the training intensity.

As we said, training intensity can be defined by the maximum heart rate of the horse. It is interesting to compare the average heart rate for a few weeks of training, for the same distance and speed. If this one decreases, it means that the fitness of the horse increases.
The maximum heart rate can be determined by the following methods (Craig and Nunan, 1998):

- An all-out trial over 1000 – 1600 m: this test is done under competition conditions.
- A continuous progressive test: this test is done with an increasing speed, over a period of 3minutes.

- A hill test: this test suggests to ride along the hill and to gradually increase the running speed, until the horse starts to tire or until we get to the top.

Resting heart rate can also give valuable information to the trainer regarding the general health status of the horse and its capacity to recover between sessions. As we previously mentioned, however, it does not decrease after a period of adequate training, contrary to men. A good way to determine it is to measure it during five consecutive days, and take the average of these values. Once the maximum and resting heart rates are known, it is interesting to delimit training zones, in order to optimize the training of the horse. Indeed, five zones can be delimited, according to the maximum heart rate.

Zone name	**Zone code**	**% of maximum HR**	**The horse taken as example**	**Example of type of activity**
Recovery	Z1	50-60%	115-138	Walk
Temperate	Z2	60-70%	138-161	Trot
Aerobic	Z3	70-80%	161-184	Canter
Threshold	Z4	80-90%	184-207	Gallop
Red zone	Z5	90-100%	207-230	Breezes

Figure 14: characteristics of the 5 training zone, Craig and Newman, 1998

Note: the suggested percentages of maximum heart rates are only approximations, and can vary according to the fitness and health status of the horse.

An interesting field test to perform while trying to improve the fitness of horses and to set training goals, is to calculate the speed at which the heart rate reaches 200bpm, or about 85% of its maximum. According to the previous table, V200 is situated in the aerobic zone.
Craig and Newman suggested the following protocol in order to calculate it: Three submaximal runs, with each time a heart rate reaching a value between 120 and 210bpm. The running distances would be between 800m to 1000m at a speed of 3.6 to 13.3 meters/second.

ThoroEdge® racing Performance Company from Kentucky also proposed to use V200 to determine what we call the Ideal Gallop Pace. Indeed, once V200 is identified, it is interesting to calculate which speed places the horse in a certain heart rate zone, and according to this, in which category the horse should compete.

- Under 20mph - not yet ready to compete
- 20-22mph - bottom level claimer
- 22-24mph - $10k claimer
- 24-25mph - $25k claimer
- 26-27mph – allowance
- 28-30mph - stakes level
- Over 30mph - graded stakes performer

GALLOPS	V200 mph	Threshold Lick	Aerobic Lick	Recovery Lick
Charlie	26.2	2:28	3:33	4:40
Green Forest	26.1	2:30	3:35	4:42
Duty Free	25.5	2:33	3:37	4:50
Dry River	24.9	2:37	3:41	4:55
Lilly	24.3	2:41	3:42	4:56
Doctor Know	23.7	2:45	3:43	4:57
Donna G	23.4	2:47	3:44	5:00
Aged	23.3	2:48	3:45	5:02
Tattoo	23.3	2:48	3:45	5:02
Zen Master	20.6	3:10	4:19	5:30
Punky One	19.1	3:24	4:50	5:55
Danny Boy	16.3	4:00	5:07	6:15

Figure 15: V200 data from a local stable, and the corresponding paces required for ideal stamina development. ThoroEdge® website, < https://thoroedge.com/is_your_horse_fit_>

Controlled warm-down periods should also be conducted after each training session in order to avoid stiffness and soreness. Indeed, an intense training will promote the build-up of lactic acid, and an appropriate time spent trotting and walking will increase the rate at which lactate is removed.

Finally, an interesting data to be evaluated is the recovery heart rate. Craig and Newman in 1998 stated the following values:

> "Horse's heart rate should return to less than 45bpm within 20minutes after trotting, 40minutes after galloping and 60minutes after breezing. It was suggested if the heart rate is not within this range, or shows a marked variation from a normal recovery pattern, the horse may be either markedly fatigued or suffering from some musculoskeletal or internal ailment that might be preventing recovery."

The following table has been made for the users of the Equimetre device, to help them to understand and assess the level of performance of their horses.

% HR max	HR level corresponding	Recovery index	Details
>55%	125 bpm	**VERY POOR**	The horse is not yet able to recover easily from the exercise. It may be a young horse that has not run yet.
55%> x > 40%	125 bpm > x > 90bpm	**POOR**	The horse is struggling to recover from the exercise, it was too intense.
40% > x > 30%	90 pbm >x > 70 bpm	**GOOD**	The horse recovers correctly from exercise, it is in good physical condition.
< 30%	<70 bpm	**VERY GOOD**	The horse is perfectly able to recover from the exercise. The training was not too intense.

Figure 16: indication of recovery threshold after 15min, Arioneo template, 2019.

Diet has also an important role in muscle fatigue, and can contribute to the accumulation of lactic acid and ammonia that occurs in the muscle when glycogen is used as energy source. During aerobic conditions, depletion of glycogen can easily happen, and a fat supplemented diet could be recommended to sustain muscle work.

Minerals and vitamins should be part of the diet, as they contribute to skeletal maintenance. As blood supplies nutrients to both bones and muscles, Vitamin B12, B1 (thiamin) can be considered as diet supplements. Increase of blood volume is correlated with age and conditioning, leading to an increase of oxygen capacity due to an efficient splenic contraction. Calcium/phosphorus ratio should be examined carefully, in order to maintain bone remodeling and skeletal integrity. The total daily diet should always contain more calcium than phosphorus. The electrolyte balance should also always be watched, because in case of sweating the loss in sodium, potassium and chloride is important. Horse muscles contain 75% of water, and sweating will induce a reduction of the blood volume. The blood will then get thicker, and its circulation is affected. Consequently the cardiac output will be reduced, the muscles will be less oxygenated, and a longer recovery heart rate can be recorded. Constant hydration of the athletes is thus vital.

An ideal body condition should always be the goal. A body condition of 5 will be in favor of best performance (on a scale of 1 to 9, with a body score of 1 synonym of poor condition, and 9 an extremely fat horse) as these horses are able to store more usable energy, and are more prone to dissipate energy and cool themselves (Gibbs *et al*., 1995).

If horses are at rest for a few weeks, we call it detraining. In 1996, Kriz and Rose said that the cardiovascular system´s fitness will decline during the first 4 to 6 weeks of rest. Bone and musculoskeletal strength seems to decrease at a slower rate than cardiovascular fitness, but are also apparently slower to recover after long periods of inactivity (Sigler, 2012).
Retraining occurs after a lay-off, and should be approached differently according to the reason of the lay-off. If a horse was not injured, but simply out of training for a year or more, we consider him as «an unfit horse" (Sigler, 2012). If the horse was injured, retraining should be more gradual, in order to give the time necessary for bone conditioning. The key of a successful retraining, as for an initial conditioning for a young horse, is to give it time!

3 Materials and methods

3.1 Arioneo Company and its Equimetre® device

Presentation of the equipment and its application

Arioneo is a French start-up company, founded in 2014. They wanted to meet the growing demand of the equine industry: the need of reliable tools to assess the behavior, health and performance of horses. They started by creating a model of sensors, named Orscana®, which goes under the blanket and can transmit on an app downloaded on the user's phone, via Bluetooth, datas like temperature, humidity and movements.

It helps to know which blanket is the most appropriate in the stable, in the field, or during transport. It is also able to analyze the movements of the horse, like the time he spent lying down, or if to the contrary, he had an agitated night.

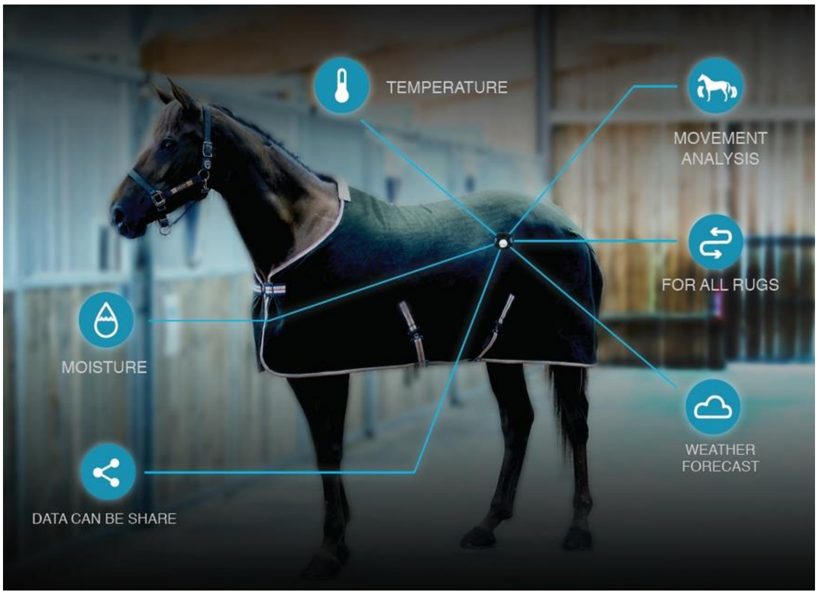


Figure 17: presentation of the Orscana® sensor, positioned under the horse blanket. Picture from Arioneo website < https://www.arioneo.com/en/home/care/>, consulted the 13/10/2019

The development of Equimetre® began in 2015, with the collaboration of professionals in the equine industry in order to ensure optimal data collection quality. It is a small electronic device, fixed on the girth of the saddle.

It is composed of two electrodes: one that we place under the saddle, below the withers, and the other one is on the side of the device, at the level of the heart. These 2 patented electrodes give the heart rate of the animal. We can also find an inertial unit with an accelerometer, a gyrometer and a magnetometer. The accelerometer measures the horse's acceleration in order to determine how fast he is evolving. The gyrometer measures the speed of rotation on the transverse axis of the horse, and the magnetometer determines the spatial orientation of the horse's movements relative to the magnetic North. The purpose is to evaluate the locomotion of the horse: speed, regularity, rhythm, stride length and stride frequency. A GPS positioning system is also included. Equimetre® is sold to race horse trainers and owners interested in taking care and increasing the performance of their horses.

Figure 18: Positioning of the Equimetre® on the horse, picture from Arioneo Website <https://www.arioneo.com/en/home/>

Figure 19: Equimetre® device, photo from Arioneo Website <https://www.arioneo.com/en/home/>

At the end of the training, the collected datas are downloaded in less than 2min on the user's phone via the Arioneo® application, and are also consultable from the Arioneo platform, on a computer.

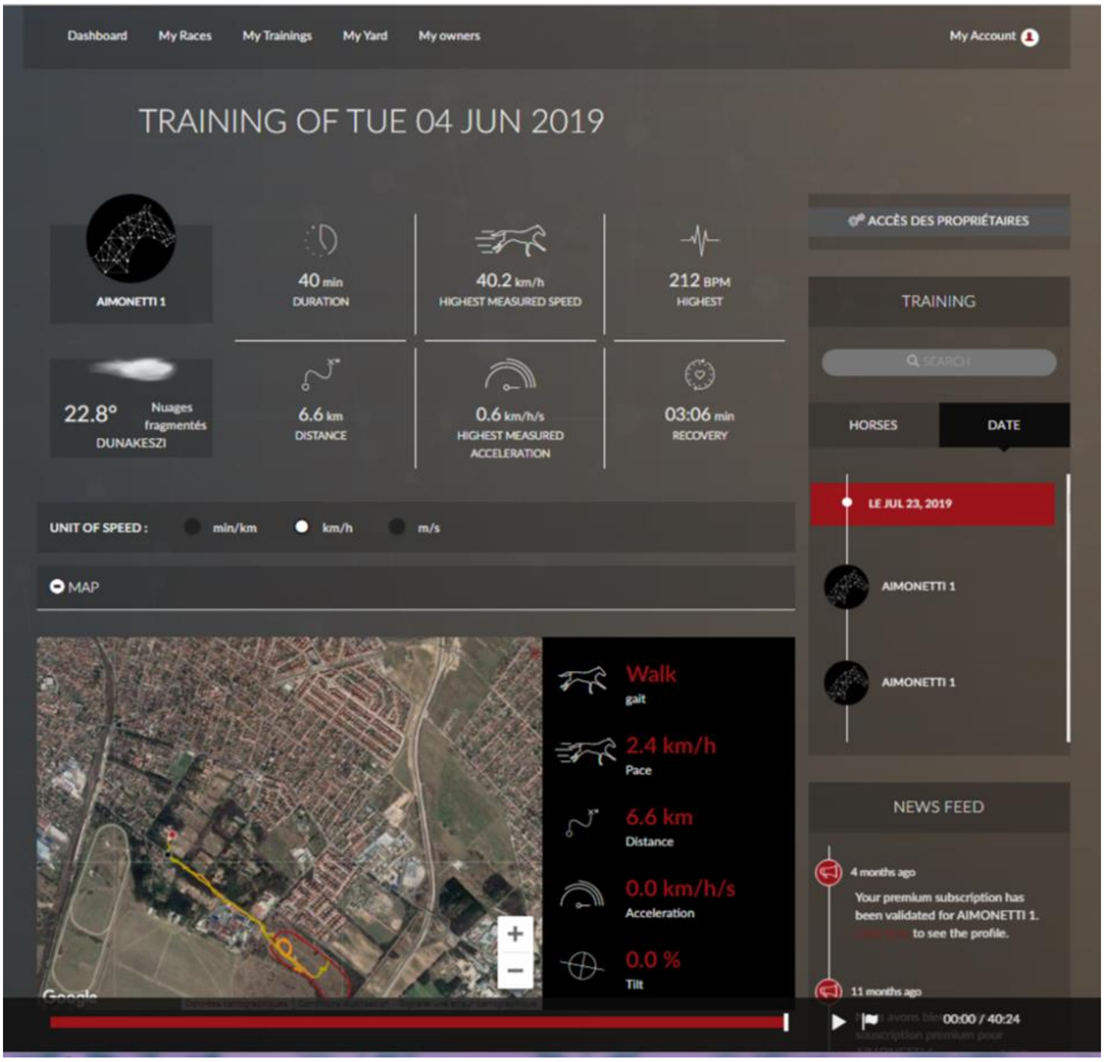


Figure 20: Arioneo platform, accessible from a computer, where the data obtained during the training are listed. (Aimonetti, 2019)

3.2 Horses

In this study, 12 horses from the same barn with the same trainer have participated and have been monitored during 2 trainings.

Horses	Age (years)	Gender	Racing level (value of the horse)	Results of the last races
Agbrand	3	Colt	V.o HP	10/10, 10/12, 10/10
Bizzottsag	3	Colt		10/12, 2/7, 2/7, 1/6, 1/4
Liquer	3	Colt	V.b HP	10/11, 7/12, 9/10, 7/13, 7/11
Matrix	8	Colt	V.o HP	2/11, 3/12, 1/13
Nart	2	Colt	Not raced	Not raced
Jubilaeum	4	Filly	II.o HP	7/7 , 5/6 , 7/11
Last stride	3	Colt	V.o HP	12/12,10/12 , 4/13, 3/10, 11/13, 8/12
Macaron	3	Colt	III.o	11/12; 5/7; 4/10; 8/13; 3/13; 5/9
Pray and Win	3	Filly	IV. Kat	6/10; 9/9; 11/12; 6/8
Riado	3	Filly	V.o HP	7/11; 4/12 ; 9/11; 2/12; 3/11; 9/12; 10/10
Tuzgalamb	4	Filly	I.o HP	4/6; 6/7; 1/8; 4/6; 3/7; 3/6
Rose fire	4	Filly	Listed	1/5; 1/5; 8/9; 5/11; 3/7; 7/8: 2/6

Figure 21: presentation of the horses used during the study, Aimonetti 2019.

<u>Explanations about the different racing levels in Hungary</u>: HP represents the handicap of the horse. We distinguish 6 different levels of handicap, from V./b to I. (first) level. The races are classified according 5 classes, from V. To I. class. Then comes the Elit (Listed) race and Grade races (best level)

3.3 Protocol

The entire study has been performed at the race horse center of Dunakeszi, in Hungary. The horses have been monitored over a time of 3months, between May and July 2019. This period corresponds to the race season, which runs from April until November. Races are usually on Saturday or Sunday. For the horses used in this study (supervised by the same trainer) the following schedule was arranged: Monday was rest, Tuesdays and Fridays are for speed work, Wednesdays and Thursdays for slow/canter work.

The horses monitored with the Equimetre® device were chosen by the trainer and were doing speed work over 1700m. Before each training, a clinical examination of the horse was performed, according to the following the exercise record sheet:

ARIONEO

Exercise record sheet:

Date and time:
Name of the horse:

Pre-training datas
Outside Temperature:

Level of hydration:

Previous training level:

Muscle stiffness evaluation:
Muscles – standpoints of the description:
• Inspection
-shape, volume (swelling, hypertrophy, atrophy)
- Symmetry
-fibrillar contractions, tic, clonus

• Palpation
-temperature
- Consistency (pasty-like, firm etc.)
- Lumps (hematoma, abscess, neoplasm)
- tone (resistance for passive motion)
- Pain

• Skin: intactness, temperature, sensitivity
RR:

Datas recorded during training
RR:
HR:
Max Speed:
Stride:
V160:
V200:

Post training datas
Muscle stiffness evaluation
RR:
Recovery HR:
Other comments:

Figure 22: exercise record sheet filled for each horse before monitored training with Equimetre®; (Aimonetti, 2019)

3.4 Experimental conditions

Type of training tracks

At the Dunakeszi race center, 3 types of races tracks are present and used for the training of the horses. The first one is called the “Summer track “, has a length of 2.800 meters and has a 4-season’s polytrack material. The second one is called the “Winter track”, has a length of 1.900 meters and is made of sand. The third track has a length of 1.200 meters, is made also of sand but is deeper than the “Winter track”. Horses were alternating their trainings on these different tracks. For the study, the horses were trained on the winter track.

3.5 Heart rate monitoring and post exercise recovery time

The Equimetre® device allows to record a continue ECG, and translate it in heart rate according to the time. The recovery time is calculated by the software, and corresponds to the time for the heart rate to drop below 120 bpm. Few phases of the recovery can actually be differentiated, and assessed by the device. Indeed, we distinguish the fast recovery phase, happening directly at the end of the intense phase of exercise, from the slow recovery phase, which take place once the heart rate is stabilized. In this study, we decided to look at the heart rate 15min after exercising.

Figure 23: Speed, Heart rate, Stride length and stride frequency parameters collected and analyzed by the Arioneo software (Aimonetti, 2019)

3.6 Locomotor parameters monitoring

Velocity, Stride length and stride frequency are extracted directly from the memory of the device, and the mean values are calculated by Python® software. These 2 parameters are also presented in figure 12.

Stride frequency (SF): is defined as the number of stride/unit time and is also equal to the inverse of stride duration. SF is usually expressed in stride/s or in hertz (Hz) and is measured by finding the frequency of the main peak of the power spectrum (1 x SF or 2 x SF) calculated by a Fast Fourier Transform (FFT) of the dorsoventral acceleration signal.

Velocity (V): is calculated every second according to the GPS datas.

Stride Length (SL): calculated by the following formula V/SF

Stride regularity (REG): Regularity is a coefficient of correlation corresponding to a peak of the autocorrelation function of the dorsoventral acceleration measured at a time equal to stride duration. It measures the acceleration pattern similarity of successive strides in the course of time.

3.7 Statistics

A statistical analysis was realized on the parameters measured, physiological on one hand and biomechanical on the other hand, using the statistical software R. The Mann Whitney test was applied. The assumption of a true link between the parameters were associated with a significance level of 0.05. The threshold of 0.10 qualified a trend.

4 Results

4.1 Physiological parameters

24 speed work trainings over 1700m have been monitored with the Equimetre® device. For each horse, the zone in which they exercised had been identified based on figure 14. (Recovery zone, Temperate zone, Aerobic zone, Threshold zone, Red line zone), and the number of horses exercising in the red zone has been correlated with the heart rate 15min post exercise.

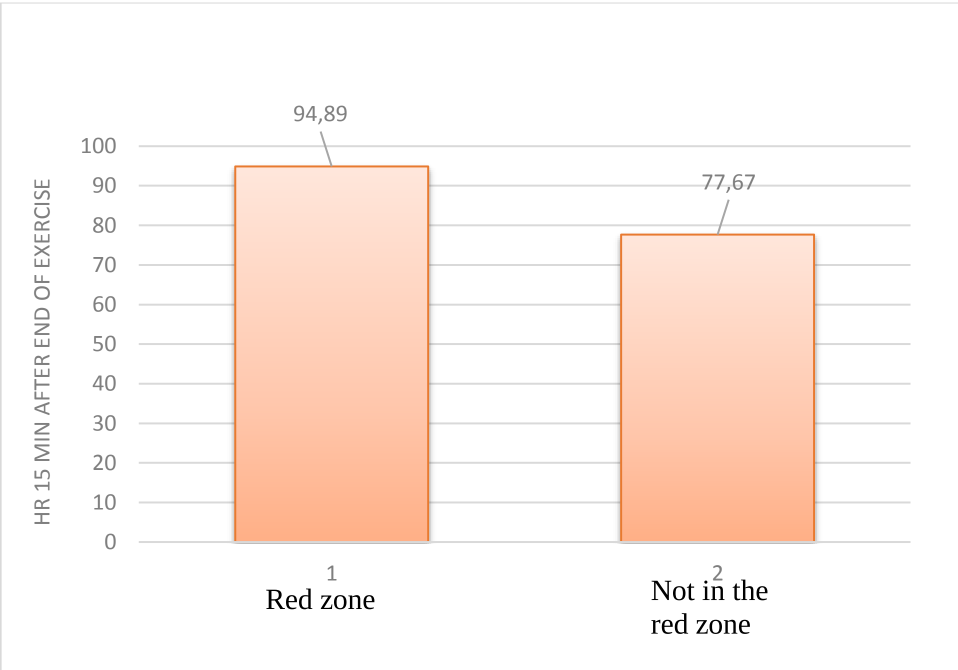


Figure 24: Graphical representation of the results obtained from the correlation between recovery time and the training zone in which the horse is exercising

Parameter 1	Parameter 2	Number of horses evaluated (n)	Mann Whitney P value	Results
Mean HR 15min after end of exercise.	Number of horses exercising in the red zone.	24	0,0299	The recovery time and the zone in which the horse is exercising is correlated. The more the horse goes under strenuous exercise the more his recovery will take longer.

Figure 25: results of the correlation between recovery time and the training zone in which the horse is exercising

4.2 Biomechanical parameters

For 15 horses, a graph representing the evolution of the speed in parallel with the evolution of the stride regularity, and the evolution of the stride regularity according to the speed have been realised.

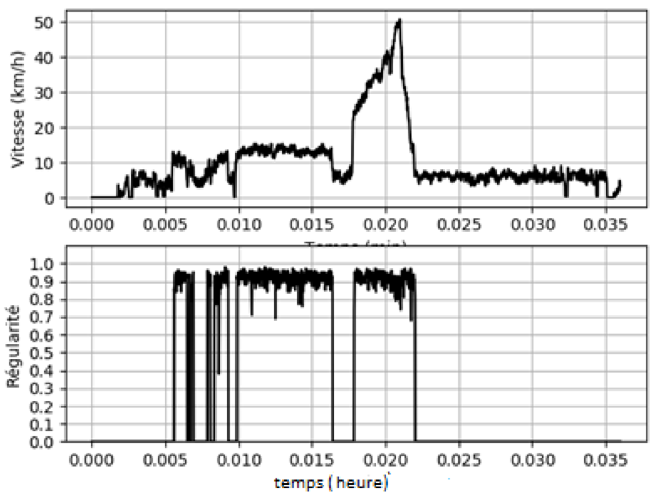


Figure 26: Evolution of the speed, in parallel with the evolution of the stride regularity, from Liquor's training.

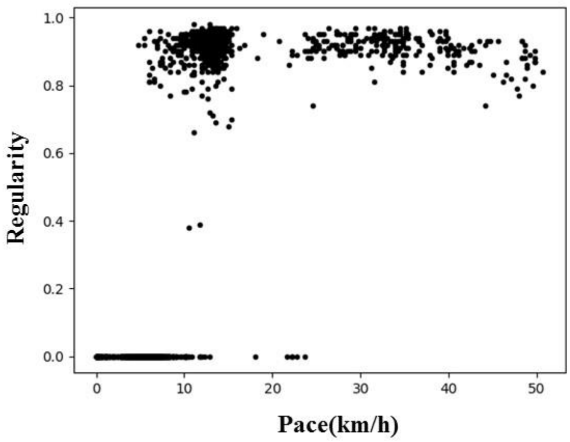


Figure 27: Evolution of the stride regularity according to the speed, from Liquor's training.

Then we correlated the regularity of the stride with the length and the frequency of the stride and obtained the following results:

Parameter 1	Parameter 2	Pearson coefficient	Mann Whitney p value	Number of horses evaluated (n)	Conclusion
Regularity of the stride	Stride frequency	+0,193327483	0,00000166	15	The regularity of the stride increases with the stride frequency
Regularity of the stride	Stride length	- 0,317374082	0,00000166	15	The regularity decreases with the stride length.

Figure 28: results obtained from the correlation of the stride regularity with the stride frequency and the stride length

4.3 Performance parameters

For each horse, few graphs have been produced:

- Correlation of speed and heart rate, according to the distance (figure 29)
- Correlation between stride length and stride frequency, according to the distance (figure 30)
- Evolution of the speed, in parallel with the evolution of the stride regularity (figure 26)
- Evolution of the stride regularity according to the speed. (figure 27)

Training of 14th of June

Liquer

Type of training: speed work 1700m

Highest HR: 220bpm

Highest speed: 48.9km/h

Recovery HR: 05min17

Figure 29: Average HR according to the covered distance. Different zones are delimited according to the HR values. From Liquor training.

Figure 30: Stride length according to the covered distance, Liquor training.

5 Discussion

5.1 Strength and Limitations of the protocol

It was unfortunately impossible to realise a real standardized test. I would have liked to realize a strict protocol, with exact warm up time and recovery bouts, but we had to adapt our self to the schedule and methods of training of the trainer. Also, the maximum speed reached during the training was different for the horses, and varied between 50km/h and 63km/h. It would be interesting to repeat the study, but this time we would set up a maximum speed to reach. The use by the rider of "Smart Watch" can guide them all along the exercise, as these watches are able to give the speed and travelled distance in real time, allowing the rider to adapt his speed to his objective.

The two main types of exercise test to evaluate the aerobic and anaerobic capacity of the horses, are laboratory exercise test (treadmill) and field exercise tests. There are 3 criteria to apply while setting an exercised test. The first one is the validity criteria, (the protocol reproduce the work required for a specific discipline). The 2nd criteria is the repeatability of the exercise, meaning that the test should reveal similar result if conducted again in a short interval of time.

The third and last criteria is the sensitivity of the test, meaning that the protocol should be able to detect small but significant changes in performance capacity. We can actually find a really good overview of the different standardized exercised protocols in the publication of De Maré et al in 2017:

Discipline / breed	Protocol	Reference
Racing Thoroughbreds (Track)	Incremental 1000m trotting at 250m/min, then galloping at 400, 460, 550, 660 m/min for 600-800m	Kobayashi et al., 1999
Racing Thoroughbreds (Track)	2-step 600m/min and 80-90% max. speed for 1038m	Von Wittke et al., 1994
Racing Thoroughbreds (Track)	Single step 1000m warm-up (slow trot), 780-960m/min (gallop, speed used in training) for 800m	Davie and Evans, 2000
Racing Thoroughbreds (Track)	Incremental warm up, 3 x 3min: canter, gallop, faster gallop + recovery periods in between Warm-up trot + fast gallops in the field al velocities of 900-960 m/min	Wolter et al., 1996
Racing Thoroughbreds (Track)	A fast exercise training session with max. speeds between 16.7 and 19.4 m/s.	Vermeulen and Evans, 2006

Figure 31: Overview of different standardized exercise protocols for racing horses. De mare, 2017.

On another hand, it was interesting to study the horses in their everyday training, without changing any of their habits. The next step would be now for each horse of the study, to establish the maximum heart rate and V200 with one of the methods described previously. Based on these datas the daily training could been restructured in order to optimize results. Another parameter interesting to test on these horses would be Vla4. Indeed, in a poorly performing horse for example, if V200 is significantly lower than VLa4, a (subclinical) musculoskeletal injury may be suspected. However, a decrease in VLa4 on the other hand is more often associated with respiratory disease. (De Maré, 2017)

5.2 Discussion of the results

Physiological parameters

Heart rate values do not seem to be an accurate mean to evaluate fitness, but should definitely be monitored, as it could indicate, whether the horse is entering a dangerous zone of rapidly appearing fatigue.

A good way to monitor fitness of a horse is to graph the heart rate response during an exercise at constant speed. The fitter the horse, the higher will be the achieved speed at the same constant heart rate. If the heart rate increases sharply during exercise, it can be a sign of injury. If early signs of injury are detected, discontinuation of the conditioning program or training is highly recommended in order to prevent irreversible injuries (Gibbs et al, 1995). Elevated heart rate can also be a sign of chronic fatigue or overtraining, for which rest should be recommended.

A horse exercising at 80% or more of his maximum heart rate exercise is in the so called red zone, and see his recovery time increased. But as we mentioned previously in the thesis, the maximum heart rate of a horse does not seem to change with the fitness level of the horse. Then our goal to enhance performance of these horses would be to decrease their cardiac recovery time, or for the same high speed to reduce their heart rate, by increasing their level of fitness.

Indeed, a longer recovery time ca be synonym of a not appropriate physical condition. We need to rule out any other pathological clinical condition. If nothing comes out, an adjustment of the training schedule should be considered. In such situation, it can be interesting to go back to the basis, and start to train again the horse as a "Young horse": The following example and idea of training is given by Freeman and al in 2003:

Long, slow distance work during the "legging up" phase is the background of a training program. This phase is characterized by an aerobic work. The cardiovascular system should conditions itself to exercise and the musculoskeletal system build up its tolerance to the stress of exercise. HR should be maintained in between 150 and 170bpm, which corresponds to the anaerobic threshold. The more the horse becomes fit, the more the speed will be elevated for the same HR.

Recovery HR should also be considered, and will occurs faster as the horse becomes more fit. A horse in good aerobic conditions will have a HR around 100bpm at 2min post exercise, and at 10min post exercise, it should be less than 60bpm.

Once the horse has a solid background, the 2^{nd} phase of training can start. It is called the "breezing phase": sprint type exercise**.** It is characterized by an exercise of *shorter duration but a more elevated speed.* HR should be in between 170 and 190bpm during this anaerobic work. Speed should be decreased if the HR goes above this threshold. Recovery HR should be 120bpm in 2min after end of exercise, and 60bpm after 10min.

A last type of training would be the so called **Interval training**. It is realized during the sharpening phase, and consist of serial sprints, interspaced with relief periods. During each sprint, the HR should be near its max value, (above 190) and in between 2 sprints it should drops to 130- 140 bpm and before starting again, should be at 120bpm. If that is not the case, risk of fatigue is high, and the horse should be warmed down.
As the horse becomes more and more fit, the speed of the sprints increase and he will be able to handle longer distance with the same HR response.

Biomechanical parameters

In this study, we demonstrated that the regularity of the stride is proportional with the stride frequency, but inversely proportional with the stride length. As mentioned previously in the thesis a combination of high length stride and frequency is an indicator of top class horses. We should not forget that a horse cannot keep up during the whole race a too high speed, and it would be interesting to evaluate, at which portion of the race a horse can hit those peak figures. However, by increasing the stride length, we will lose regularity.

We also know that horses have a specific breathing pattern, known as locomotor-respiratory coupling (LRC), in which respiration is "*driven by the locomotor forces associated with weight bearing on the front limbs, the pressure of the abdominal organs against the diaphragm and changes in orientation of the body axis. These factors are gait dependent and as a result LRC is most effective in canter and gallop where there is a strict 1:1 ratio between the respiratory and locomotor cycle"(* Firshman, 2010). Indeed, we know that the diaphragm is the principal movement of inspiration, and his movements is accentuated by the movements of the visceral organs known as the “visceral piston”. When the forelimbs hit the ground, expiration happens, and when the forelimbs are in the suspension phase, inspiration is stimulated. When the stride is constant, it allows the visceral piston to settle into the stride rhythm, allowing the energetic cost of breathing to be reduced to the minimum. Therefore, each time the stride length of the horse become irregular by a change in frequency or length, is has an energetic price for the horse. The goal is then to try to maintain a regular rhythm. Plus we should keep in mind that a short stride length will affect the tidal volume, by giving less time for inspiration. (Firshman, 2010)

Performance parameters

Let’s analyse the figures 29 and 30, as example of training monitored by the Equimetre device:

Zone A represents the work zone of the horse. According to figure 14, it would seem that Liquor is exercising in the red zone, if we consider that his HR max is around 230 bpm. It would be interesting to define it precisely, by the method proposed earlier in this thesis. The stride length increases regularly during 1000m, then we can observe a slight decrease before the last push. His racing results are not really good, and the recovery time elevated.

At the end of exercise, the speed decreases significantly, the heart rate must follow this decrease. We call it the deceleration zone at the end of training (zone B). However, it can remain high in order to compensate for the oxygen debt accumulated during effort. The duration of this zone characterizes how hard the exercise was relatively to the physical condition of the horse and its ability to recover. The shorter is the area, the more the performance and the tolerance of the horse is important.

Indeed, if the heart rate decreases rapidly at the end of the effort, it means that the horse coped well with the exercise.

However, if the heart rate of the horse continues to increase slightly at the end of the exercise, it shows that this exercise was difficult for him. *This tendency is seen in most of the horses of our study, and it is also the case of Liquor, figure 29.*

Then comes the “rapid recovery phase “(zone C). Here the heart rate decreases very rapidly over a few seconds. This zone is characteristic of the recovery of the parasympathetic nervous system, responsible for slowing down the heart rate.

The last zone is called the “slow recovery phase” (zone D), where the heart rate should keep decreasing slowly and stabilize itself.

As we already mentioned it earlier in this thesis, it has been shown that the recovery time can be correlated with the level of performance of the horse: the lower it is, the fitter is the horse. The closer it is to the base frequency, the more the horse have recovered from the work session. An increased recovery time is not innocuous, and if this situation is observed over a few trainings, the horse should be watched carefully for signs of fatigue, and assessed for any cardiopulmonary disorder or other pathologies.

5.3 Continuity and orientation for the future

It would also have been interesting to study the cardiac variability parameters; as they are also given by the Equimetre® device. They are not yet accessible on the platform by the user, but raw datas can be extracted and studied, such as:

TI: Triangular index;

TIRR: Triangular interpolation of the R-R interval;

SD1: Quantifying the dispersal of data points in a point carré plot perpendicular to the line of identity;

SD2: Quantifying the dispersal of data points in a Point carré plot along the line of identity;

Studies have been conducted on humans, and showed that cardiac variability can be used as a marker of cardio metabolic risk in public health (Marsac, 2013), and are commonly used in humans as an early marker of fatigue (Cassirame, 2015).

On another hand, studies on horses are planned by the College des Hautes Etudes Lyon Science[s] (CHEL[s]). Their first task is to conduct a field study to determine the correlation between cardiac variability and well-being in cases of overtraining, pain, and stress in the horse. This will be a really interesting study, as these cardiac variability parameters can be calculated and given by non-invasive method, thanks to the connected devices developed by the different companies, and will give us priceless information’s about the general health state and training level of the horses.

A new device has been recently launched by Arioneo Company, the EQUIMETRE VET®. It is similar to the device used for this study, but this one is addressed particularly to the research and veterinary community. The evaluated parameters are the same as with Equimetre® (heart rate, speed, distance, stride length; stride frequency), but the innovation is that a complete electrocardiogram (ECG) is provided and analyzed by Kubios® software. This can be used to establish a diagnosis of cardiac arrhythmia, or other cardiac pathologies. Moreover, as Dr. Dubois, scientific director of Arioneo said, the *"unparalleled mass of data aggregated by our sensors opens new perspectives in matter of research*", and hopefully would lead to new discoveries in subjects of cardiology, genetic and training.

We could also imagine that in a near future, the official veterinarian of a race stud would get daily notifications on his phone for each horse his is following, and an alert would prevent him in case of detection of abnormal datas during the training. Pathologies could be prevented, disasters avoided and performance optimized.

Another really interesting new technology has been introduced recently by Dr. Sheila Lyons, DVM, and founder of The American College of Veterinary Sports Medicine and Rehabilitation, for the safety of racehorses:

> "The American College of Veterinary Sports Medicine and Rehabilitation is committed to the highest standards of ethics and integrity for veterinary services for all animals. It is opposed to the use of any performance enhancing or injury masking drugs used during training and competition for all animal athletes or animals in service. It promotes and contributes to scientific advancement and encourages veterinary practices to be strictly limited to those which improve or protect the health, fitness and well-being of animal" (acvsmr website, 2019)

She developed a high resolution Three-Dimensional CT scanner for horses along with Curvebeam, LLC. This scanner allows the patient to stand while the images are taken, allowing the clinician to analyze the stressed areas of bone while under loading pressure. There is no need of anesthesia only slight sedation is needed. In less than 48 seconds it scans both front and hindlimbs. Knowing that 90% of the fatally injury horses had subchondral pathology pre-existing in the area which fractured, if a scan is realized on young horses before they enter the racetrack, and then if they are monitored once a year, fatal injuries could be avoided (Berner, 2019).

Lesions undetectable on X rays would be now noticeable, and horses prone to fatal injuries would be kept away from the racetrack. Indeed, repetitive cyclic stress to the skeleton is also one of the primary cause of lameness in racehorses, and almost all fractures in race horses are due to stress.

Racehorses present a lot of pathologies along their musculo-skeletal system - a system which requires the most training and sustains the most wear and tear. The skeleton of the future athlete has literally to be molded into a *"performance skeleton"* (Bramlange, 2013). Selective breeding and exercise will induce skeletal modeling. Adaptive training will result in skeletal modeling and re-modeling, which is work specific. Finally, we should not forget that any exercise debt must be paid, whether it is in matter of cardio, respiratory, musculo-skeletal modeling. Rest can be the appropriate solution in mild cases of pathologies.

6 Conclusion

This study demonstrated that the regularity of the stride is proportional with the stride frequency, but inversely proportional with the stride length. It was also shown that a horse exercising at approximately more than 80% of his maximum heart rate will see his recovery time increased.

We can conclude that the use of the Equimetre device can be a great help for trainers, to monitor the training of race horses, in order to improve performance on one hand, and to detect fatigue and risk of overtraining.

Veterinary usage can also be considered, especially in case of poor performance horses. In addition to clinical and laboratory examination, this device can definitely help to assess cardiac and locomotor parameters of horses during their training, and help with the final diagnosis.

7 References

Work about Equine Physiology:

Books

HINCHCLIFF, K.W., KANEPS, A. J., GEOR, R.J. 2008. *Equine exercise physiology: the science of exercise in the athletic horse*. Elsevier Health Sciences. p. 476.

HINCHCLIFF, K.W., KANEPS, A. J., GEOR, R.J. 2013. *Equine Sports Medicine and Surgery E-Book: Basic and clinical sciences of the equine athlete*. Elsevier Health Sciences. p. 1374.

HODGSON, D.R., MCGOWAN, C.M., MCKEEVER, K. 2013. *The athletic horse: principles and practice of equine sports medicine.* Elsevier Health Sciences. p. 408.

SOUTHWOOD, L., WILKINS, P.A. 2014. *Equine emergency and critical care medicine*. CRC Press. p. 880.

Articles:

BAYLY, W. M., GRANT, B. D., BREEZE, R. G., et al. 1983. The effects of maximal exercise on acid-base balance and arterial blood gas tension in Thoroughbred horses. *Equine exercise physiology*, vol. 1, p. 400-407.

BAYLY, W. M., WARWICK M., SCHULTZ, D. A., HODGSON, DAVID R., et al. 1987. Ventilatory responses of the horse to exercise: effect of gas collection systems. *Journal of Applied Physiology*, vol. 63, no 3, p. 1210-1217.

BERNER, M. 2019. Technology can help get horse racing off drugs. Horse Race Insider website. URL: https://www.horseraceinsider.com/technology-gets-horse-racing-off-drugs/ Consulted the 01.10.2019

BRUIN, G., KUIPERS, H., KEIZER, H. A., et al. 1994. Adaptation and overtraining in horses subjected to increasing training loads. *Journal of Applied Physiology*, vol. 76, no 5, p. 1908-1913.

CARDINET, G.H., FOWLER, M. E., TYLER, W. S. 1963. Heart rates and respiratory rates for evaluating performance in horses during endurance trail ride competition. *Journal of the American Veterinary Medical Association*, vol. 143, p. 1303-1309.

CASSIRAME, J. 2015. Intérêts et limites de l'utilisation de l'analyse de la variabilité de la fréquence cardiaque pour la pratique sportive. PhD thesis subject to obtain the degree of doctor of the University of Franche Comté, Life and health Sciences specialty. URL: http://indexation.univ-fcomte.fr/nuxeo/site/esupversions/1d41399a-8922-45cf-a561-ad91e9db2946 Consulted on the 2019.10.26

DE GRAAF-ROELFSEMA, E., KEIZER, H.A., VAN BREDA, E, et al. 2007. Hormonal responses to acute exercise, training and overtraining a review with emphasis on the horse. *Veterinary Quarterly*, 2007, vol. 29, no 3, p. 82-101.

DUŠEK, J., EHRLEIN, H.J., ENGELHARDT, W., et al. 1970. Beziehungen zwischen Trittlänge, Trittfrequenz und Geschwindigkeit bei Pferden 1. *Zeitschrift für Tierzüchtung und Züchtungsbiologie*, vol. 87, no 1-4, p. 177-188.

FLAMINIO, M.J, GAUGHAN, E.M., GILLESPIE, J. 1996. Exercise intolerance in endurance horses. *Veterinary Clinics of North America: Equine Practice*, vol. 12, no 3, p. 565-580.

FRAIPONT, A., VAN ERCK, E., RAMERY, E. 2012. Assessing fitness in endurance horses. *The Canadian Veterinary Journal*, vol. 53, no 3, p. 311.

FRICK, L., SCHWARZWALD, C., and MITCHELL, K. 2019. The use of heart rate variability analysis to detect arrhythmias in horses undergoing a standard treadmill exercise test. *Journal of veterinary internal medicine*, vol. 33, no 1, p. 212-224.

HIRAGA, A., YAMANOBE, A., and KUBO, K. 1995. Relationships between stride length, stride frequency, step length and velocity at the start dash in a racehorse. *Journal of Equine Science*, vol. 5, no 4, p. 127-130.

JÄRVINEN, T.A.H., JÄRVINEN, M., KALIMO, H. 2013. Regeneration of injured skeletal muscle after the injury. *Muscles, ligaments and tendons journal*, vol. 3, no 4, p. 337.

KAI, M., KUBO, K. 1993.Respiration pause and gait after the start dash in a horse. *Bulletin of Equine Research Institute*, vol. 1993, n° 30, p. 26-29.

KOHN, C.W., HINCHCLIFF, K. W., MCCUTCHEON, L. J. 1995. Physiological responses of horses competing at a modified 1 Star 3-day-event. *Equine Veterinary Journal*, vol. 27, no S20, p. 97-104.

MARSAC, J. 2013. Variabilité de la fréquence cardiaque: un marqueur de risque cardiométabolique en santé publique. *Bulletin de l'Académie nationale de médecine*, vol. 197, no 1, p. 175-186.

PERSSON, S. G. B. 1967. On blood volume and working capacity in horses. *Acta vet. Scand*, vol. 19, p. 1-189.

PERSSON, S. G. B. and ÖSTERBERG, I. 1999. Racing performance in red blood cell hypervolemic Standardbred trotters. *Equine Veterinary Journal*, vol. 31, no S30, p. 617-620.

VALBERG, S. J., WARD, T. L., RUSH, B., et al. 2001. Glycogen branching enzyme deficiency in quarter horse foals. *Journal of veterinary internal medicine*, vol. 15, no 6, p. 572-580.

VALETTE, J. P. et WOLTER, R. 1988. Intérêt des mesures de lactatémie et de fréquence cardiaque comme critères d'aptitudes sportives. *CEREO-PA, 14e journée d'étude*, vol. 9, p. 1-16.

VERMEULEN, R., PLANCKE, L., BOSHUIZEN, B., et al. Effects of training on equine muscle physiology and muscle adaptations in response to different training approaches. *Vlaams Diergeneeskundig Tijdschrift*, 2017, vol. 86, no 4, p. 224-231.

WEERAPONG, P, HUME, P.A., KOLT, G.S. 2005. The mechanisms of massage and effects on performance, muscle recovery and injury prevention. *Sports medicine*, vol. 35, no 3, pp. 235-256.

WILSON, R.G., ISLER R.B., THORNTON J.R. 1983. Heart rate, lactic acid production and speed during a standardized exercise test in Standardbred horses. *Equine Exercise Physiology 1*, p. 487–496.

Websites:

FIRSHMAN, A. 2010: Heart rate and respirator rate response to exercise in horses. *Dvm360*, URL: http://veterinarycalendar.dvm360.com/heart-rate-and-respirator-rate-response-exercise-horses-proceedings?id=&sk=&date=&pageID=4 Consulted the 2019.10.25

Kentucky Equine Research Staff. 2010: From the heart. 2010. URL: https://ker.com/equinews/from-the-heart/ Consulted the 2019.07.07

LESTE-LASSERRE, C. 2018: Standing fibrotic myopathy surgery for horses showing promise. URL: https://thehorse.com/159234/standing-fibrotic-myopathy-surgery-for-horses-showing-promise/ Consulted the: 2019.08.25

Veterian KeyFastest Veterinary Medicine Insight Engine. 2016. Chapter 12, Muscle anatomy, physiology, and adaptations to exercise and training. URL: https://veteriankey.com/muscle-anatomy-physiology-and-adaptations-to-exercise-and-training/ Consulted the: 2019.10.06

XLSvet. Fact sheet atypical myopathy. Journal title unknown, year of publication unknown [online] URL: http://dendi.xlvets.co.uk/sites/default/files/factsheet-files/XLVets-Equine-Rebranded-114-Equine-Muscle-Disease-factsheet.pdf Consulted the: 2019.07.15

Lecture notes:

BRAMLAGE, L. Lecture *Training and the musculoskeletal system*, hold in 2O13 at the American Association of Equine Practitioners’ Convention, held Dec. 7-11 in Nashville, Tenn.

CLASSEN, S. Lecture *Introduction to Therapeutic Exercise*, hold in 2018 at an ISELP congress in Lexington, Kentucky, USA.

KUTASI, O. Equine Exercise physiology and sport medicine elective course, *Training and overtraining in horses*, hold in 2017, at the University of Veterinary Medicine in Budapest, Hungary.

Work about horse training:

Books:

CRAIG, N., NUMAN, M., 1998. *Heart rate training for horses*. Performance matters Pty Ltd, p. 7-43.

DAVIE, A. 2003. *Scientific training of Thoroughbred horses*. 2nd edition. Norsearch reprographics, southern university, p.10.

Articles:

BRUIN, G., KUIPERS, H., KEIZER, H. A., et al. 1994. Adaptation and overtraining in horses subjected to increasing training loads. *Journal of Applied Physiology*, vol. 76, no 5, p. 1908-1913.

DE MARÉ, L., BOSHUIZEN, B., PLANCKE, L., and al. 2017. Standardized exercise tests in horses: current situation and future perspectives. *Vlaams Diergeneeskundig Tijdschrift*, vol. 86, no 2, p. 63-72.

EVANS, D.L. 2000. Training and Fitness in Athletic Horses: A Report for the Rural Industries Research and Development Corporation; RIRDC *Project No. US-77a*. RIDC.

EVANS, D.L. 1995. Cardiovascular adaptations to exercise and training. *Veterinary clinics of North America: Equine practice*, vol. 1, no 3, p. 513-531.

FREEMAN, D.W., TOPLIFF, D.R., COLLIER, M.A., et al. 2003. Monitoring fitness of horses by heart rate. URL:https://shareok.org/bitstream/handle/11244/49988/oksd_ansi_9118_2003-07.pdf?sequence=1&isAllowed=y Consulted on the: 2019.10/26

GIBBS, P. G., POTTER, G. D., NIELSEN, B. D., et al. 1995. Scientific principles for conditioning race and performance horses. *The Professional Animal Scientist*, vol. 11, no 4, p. 195-203.

GOLLAND, L.C., EVANS, David L., STONE, Grant M., et al. 1999. Plasma cortisol and β-endorphin concentrations in trained and over-trained Standardbred racehorses. *Pflügers Archiv*, vol. 439, no 1-2, p. 11-17.

HAMLIN, M. J., SHEARMAN, J. P., and HOPKINS, W. G. 2002. Changes in physiological parameters in overtrained Standardbred racehorses. *Equine veterinary journal,* vol. 34, no 4, p. 383-388.

LYONS, S. 2008. Preventing injury when horse switch surfaces. *The blood horse*, no 39. URL: http://www.acvsmr.org/Blood_Horse_Cover_Article_Preventing_Injuries.pdf Consulted the 03.09.2019.

KRIZ, N. G. and ROSE, R. J. 1996. Effect of detraining on cardiac dimensions and indices of cardiac function in horses. *Proc. Annual Conv. Am. Assoc. Equine Pract,* vol. 42, p. 96.

MCGOWAN, C. M., WHITWORTH, D. J.2008. Overtraining syndrome in horses. *Comparative Exercise Physiology*, vol. 5, no 2, p. 57-65.

PERSSON, S. G. B., LARSSON, M., et LINDHOLM, A. 1980. Effects of Training on Adreno-cortical Function and Red-cell volume in Trotters 1. *Zentralblatt für Veterinärmedizin Reihe A*, vol. 27, no 4, p. 261-268.

SIGLER, D. H., 2012. Conditioning and Retraining the Equine Athlete. URL: https://agrilifecdn.tamu.edu/animalscience/files/2012/04/conditioning-and-retraining-the-equine-athlete.pdf Consulted the: 2019.10. 26

TYLER, C. M., GOLLAND, L .C. EVANS, D. L., et al. 1996. Changes in maximum oxygen uptake during prolonged training, overtraining, and detraining in horses. *Journal of Applied Physiology*, vol. 81, no 5, p. 2244-2249.

Websites:

Attheraces.com. 2018: Stride Data launched on attheraces.com. URL: https://www.attheraces.com/news/2018/February/05/stride-data-launched-on-attheraces.com Consulted the: 2019.29.08

DataTrack international, LLC. 2019. Motion & stride length analysis of race videos. URL: http://www.biodatatrack.com/motion-analysis.html Consulted the: 2019.29.08

GEOR, R. 2000: Peak Fitness. *The HORSE, your guide to equine health care*. URL: https://thehorse.com/14042/peak-fitness/ Consulted the 12.11.2019

ThoroEdge Equine Performance.2019. Is your horse FIT? URL: https://thoroedge.com/is_your_horse_fit_ Consulted the 2019. 10.09

College des Hautes Etudes Lyon Science[s]. 2017. VFC Équin – étude de la variabilité de fréquence cardiaque chez le cheval de sport. URL: http://www.chels.fr/?p=1924 Consulted the: 26.10.2019

The American College of Veterinary Sports Medicine and Rehabilitation (ACVMR). 2019. Home page. URL: http://www.acvsmr.org/ Consulted the 14.10.2019

Work about human training:

FRY, A.C., SCHILLING, B.K., WEISS, L.W., *et al*. 2006. B2-Adrenergic receptor downregulation and performance decrements during high-intensity resistance exercise overtraining. *Journal of Applied Physiology*, vol. 101, no 6, p. 1664-1672.

JÄRVINEN, T., JÄRVINEN, M., et KALIMO, H. 2013. Regeneration of injured skeletal muscle after the injury. *Muscles, ligaments and tendons journal*, vol. 3, no 4, p. 337.

KUIPERS, H. and KEIZER, H. A. Overtraining in elite athletes. 1998. *Sports Medicine*, vol. 6, no 2, p. 79-92.

.

8 Appendices

Few examples of trainings monitored with the Equimetre device are showed in the following pages.

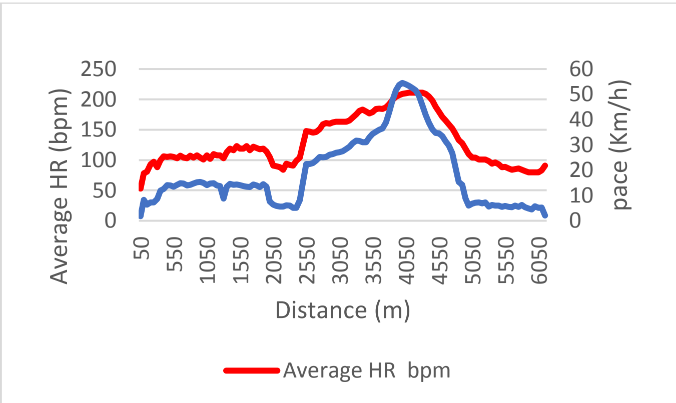
Training of the 21st of June, 05:26 am

Jubilaeum

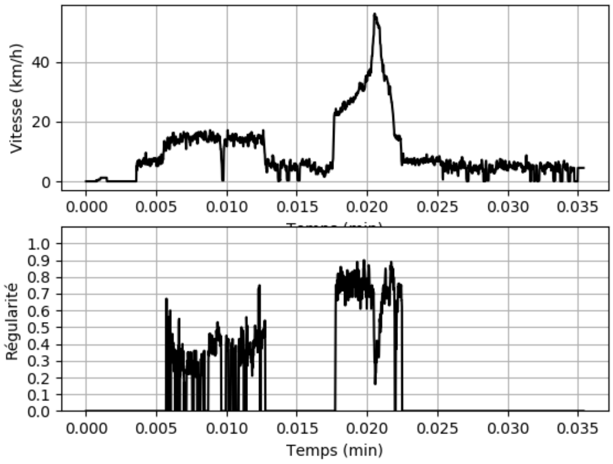
Clinical examination:

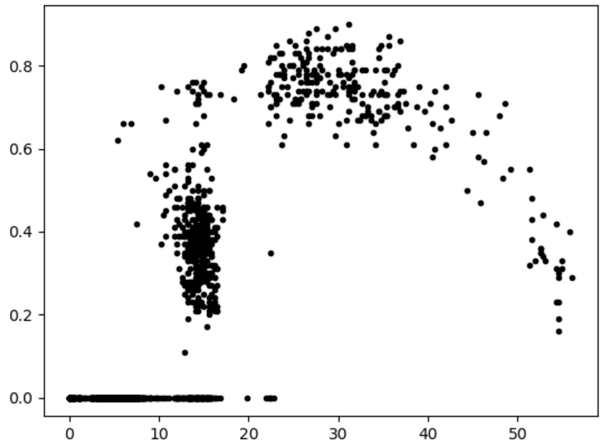
- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency, OK, no lumps, muscle tone OK, no pain apparent

General observation: When started to warm up trotting, horse was really stiff, with short stride and seemed uncomfortable, but No obvious lameness
Training: short distance high speed, to prepare 2days before the race 1700m, with sprint on the last 250m "breezing phase"
Highest HR: 212bpm
Highest speed: 54.6km/h
Recovery HR: 03min40



Graph analysis:
The recovery time is quite good, and the stride length increases in correlation with the speed increase.
Same as for the other horses, it would have been interesting to define correctly the HRmax, in order to identify in which zone our horse is. According to figure 14, if we make the hypothesis that Jubilaeum HR max is around 230 bpm, and consequently he is exercising already in the red zone.





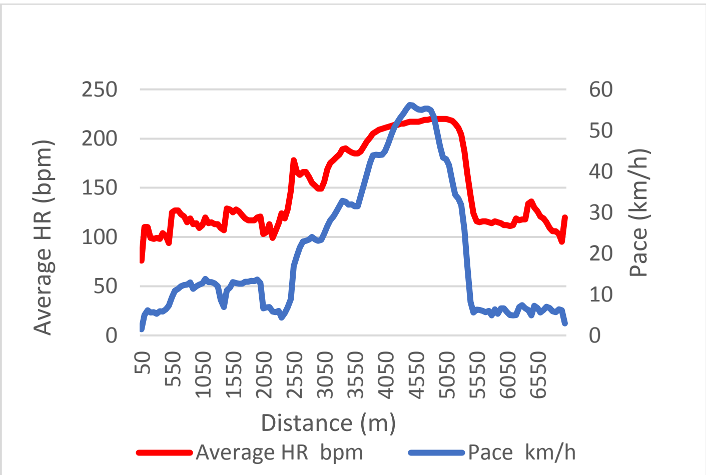
Training of the 25th of June   07:36am

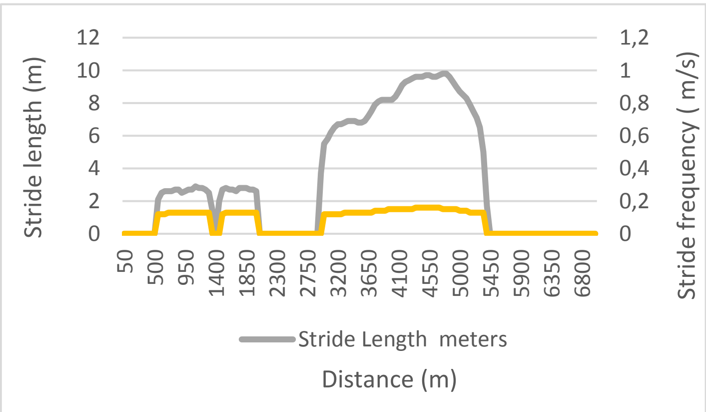
Clinical examination:

- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency OK, no lumps, muscle tone, no pain apparent

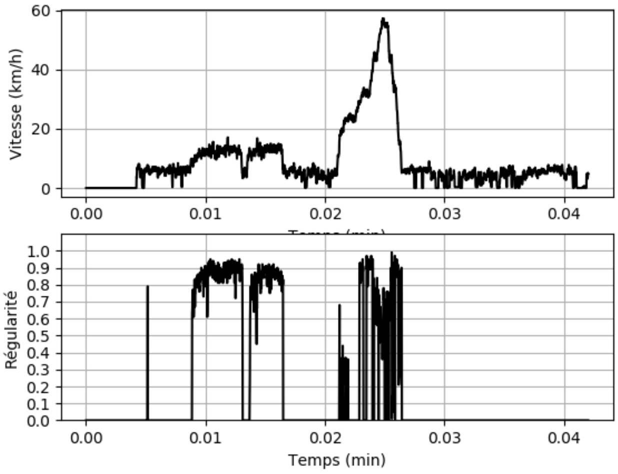
General observation: horse still a bit stiff, but better general locomotion.
Training: short distance high speed, 1700 m

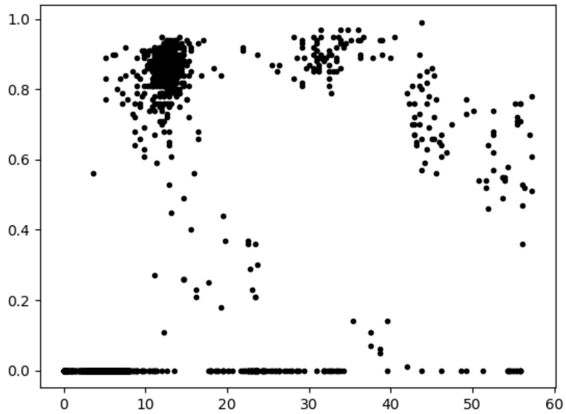
Highest HR: 220pbm
Highest speed: 56.4km/h
Recovery HR: 04min04





Graph analysis: The distance covered during this training was a slightly longer than during the previous training. Speed max was 2km/h higher, and the recovery heart rate also a bit longer. If we still consider his HRmax around 230, Jubilaeum is again exercising in the red zone. His racing results are not satisfying, and we might recommend some rest. The stride length seems incorrect, reaching almost 10m…





Training of the 12th of July

Abraham

Clinical examination:

- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency, OK, no lumps, muscle tone OK, no pain apparent, no fremitus

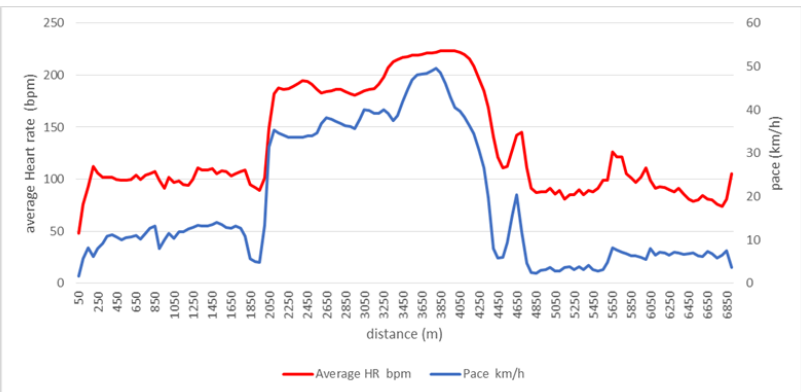
General observation:

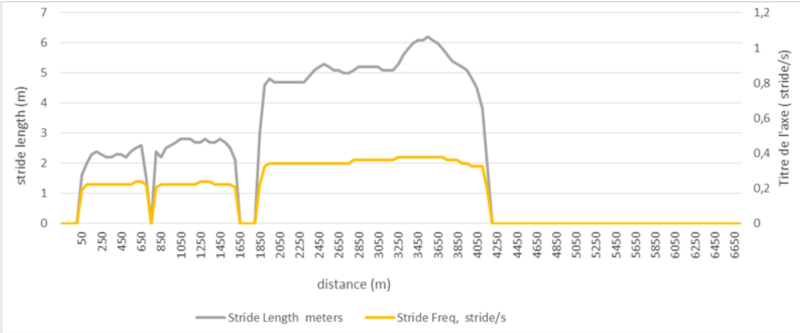
Training: speed work

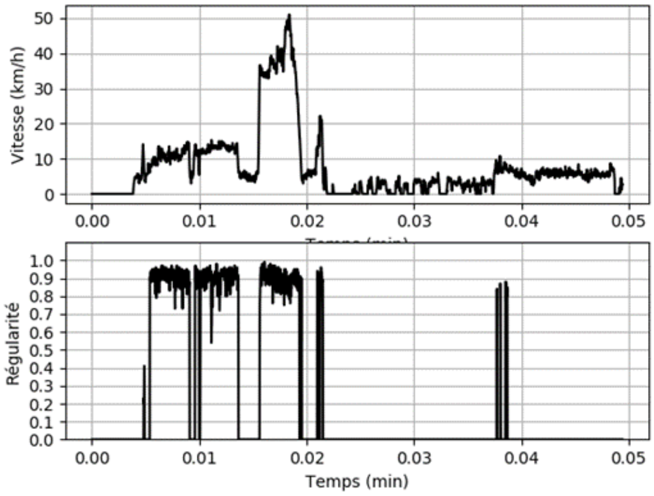
Highest HR: 223bpm

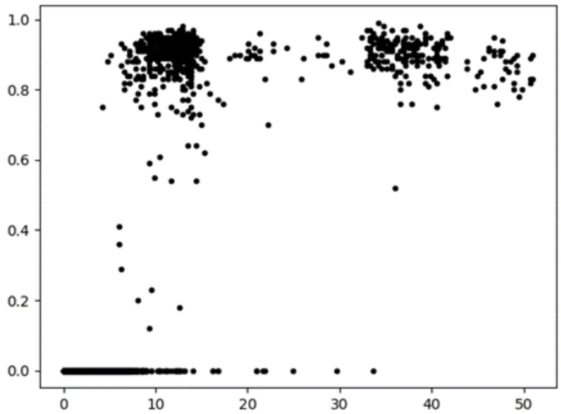
Highest speed: 49.8km/h

Recovery HR: 06:03min









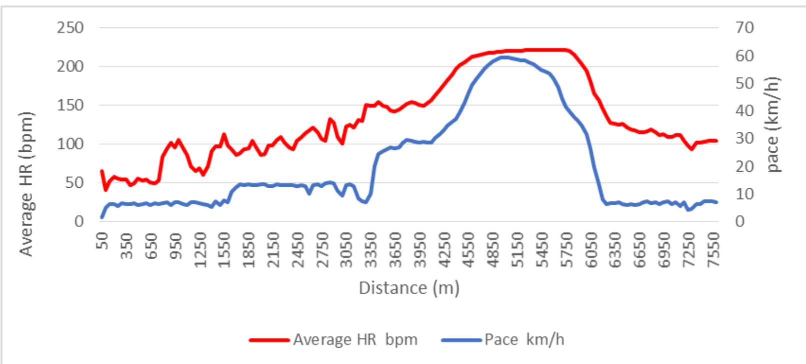
Training of the 25th of June

BIZOTTSAG

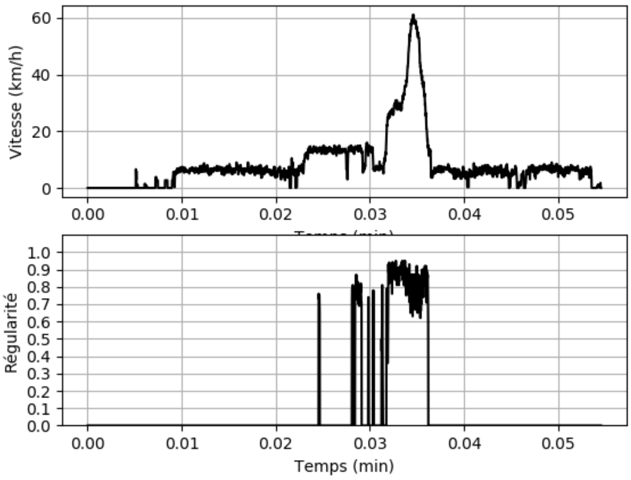
Clinical examination:

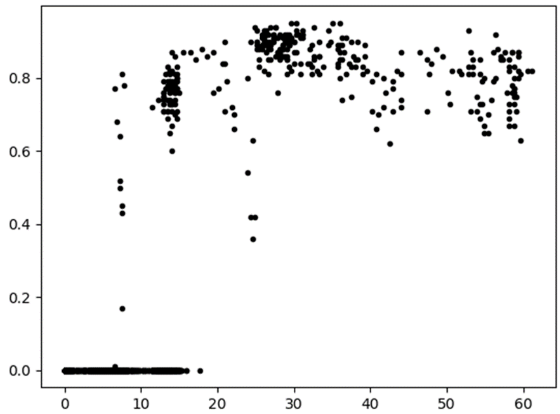
- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency, OK, no lumps, muscle tone OK, no pain apparent

General observation: slightly stiff walk when walking out of the stable.
Training: Speed work on the big track
Highest HR: 223bpm
Highest speed: 59.4km/h
Recovery HR: 04min45



Graph analysis: HR stays elevated even after the end of the effort, which can be a sign of beginning of fatigue, too intense training, cardiac-pulmonary system not developed enough, perhaps because intense training started too early, and indeed, the recovery HR time is a bit long.
It would be interesting to come back to aerobic training for a while.
Her racing results are quite ok, and shows some potential.





Training of the 11th of July

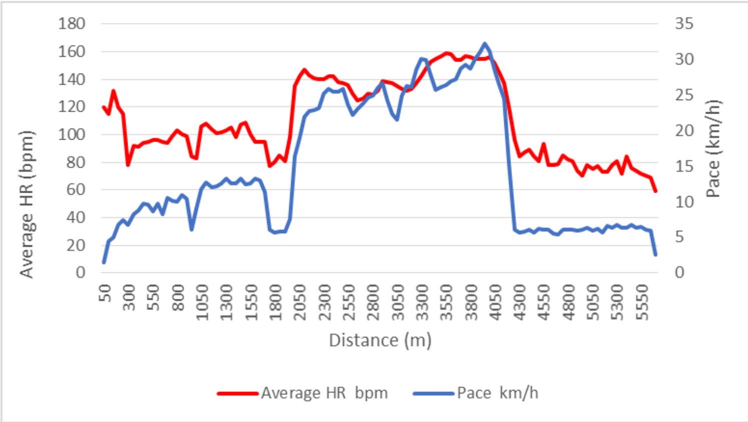
LAST RIDE

Clinical examination:

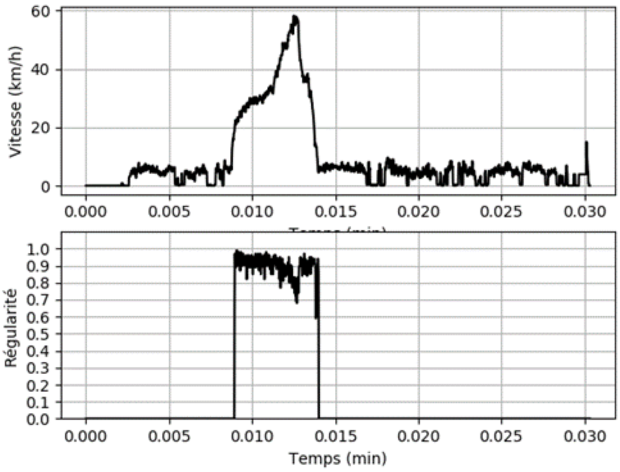
- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency OK, no lumps, muscle tone, no pain apparent

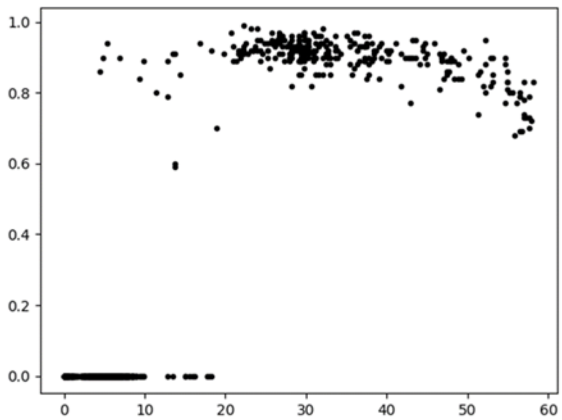
General observation: horse walking a bit stiff while going out of the barn.

Training: Canter 1700m
Highest HR: 159pbm
Highest speed: 32.4km/h
Recovery HR: 03min20



Graph analysis: Interesting training, this horse was evaluated during a slow canter. According to figure 14 , our horse is exercising in the aerobic zone, at approximately 70 to 80% of its maximum HR. The recovery heart rate is correct, and the stride length is also in the average. However, speed, HR and stride length are a bit irregular.





TUZGALAMB

Training of the 16th of July

Clinical examination:

- Muscle inspection: shape, volume, symmetry OK
- Muscle palpation: Temperature, consistency, OK, no lumps, muscle tone OK, no pain apparent

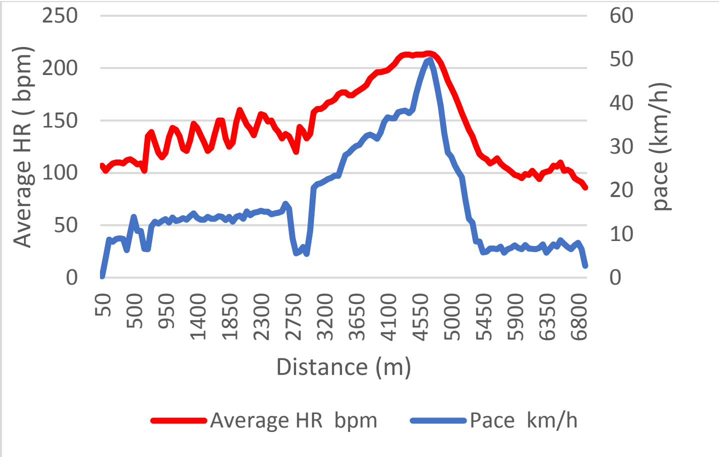
General observation: mare does not look in great shape, not really harmonious

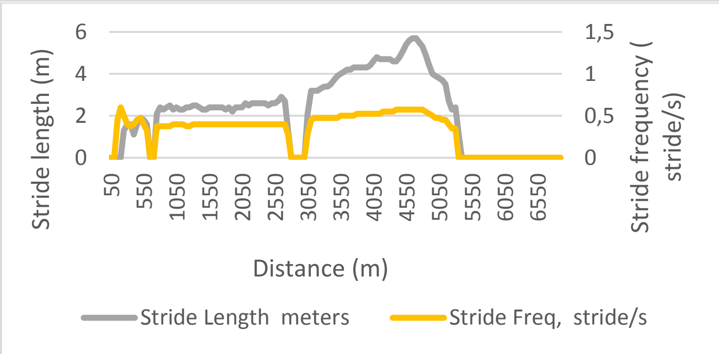
Training: speed work 1700m

Highest HR: 214 bpm

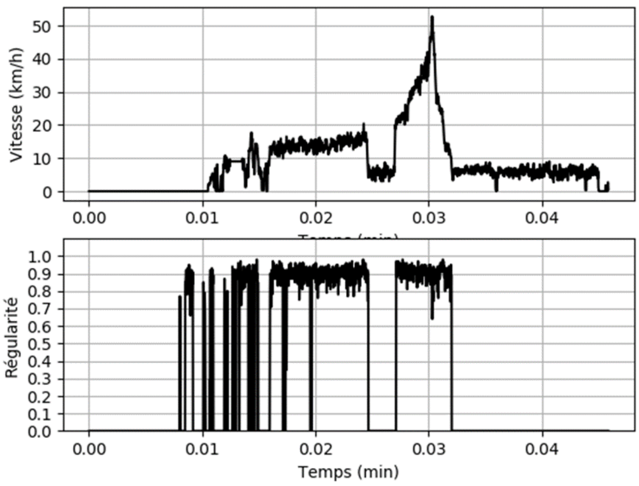
Highest speed: 50.1 km/h

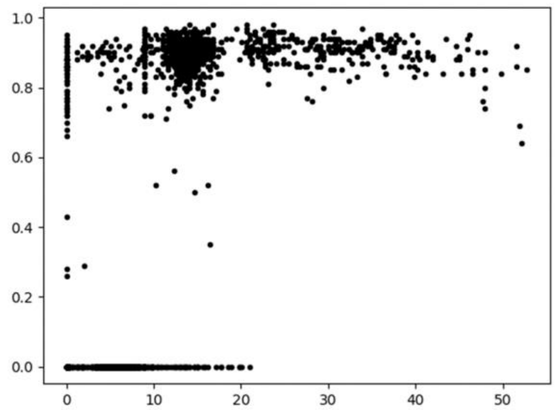
Recovery HR: 06:11min





<u>Graph analysis:</u> Really long recovery HR. Irregular HR during first part of work.





9 Acknowledgement

To Dr. Gerics,

My thesis supervisor,

For his guidance and wise advices. For believing in this project, while it was just a seed, and making it come true.

Respectful acknowledgment and gratitude.

To Mr. Dubois

Scientific direct of Arioneo Company,

For his trust, unconditional patience and help all along these last months. This thesis would have not been realized without his precious help and collaboration.

Truthful gratitude.

To Attila Rácz,

Horse trainer at Dunakeszi racing center,

For his everyday investment in this study, for lending me his horses, for his precious and bright advices, and for his translations from hungarian to english language!

Sincere gratitude.

To Ferenc Csupor,

Horse trainer at Dunakeszi racing center,

For his kindness, patience, and for lending me his horses for the study.

Sincere gratitude.

To my fiancé,

For his constant support and love, and for believing in me every single day.

Thank you.

To my family,

For their generosity and support since all these years. For allowing me to realize my dream to become a veterinarian.

Eternal gratitude.

To my friends Sami, Olivier and Lucie,

For your precious advises and corrections all along the redaction of this thesis. This study would not have seen the daylight without your help.

Sincere gratitude.

10 Abstract

Reasons for performing the study: Safety and top-level training are equally important to achieve the best athletic performance of the race horse. Along increasing daily training-load the responsiveness of the horse and improvement in fitness should be monitored. The use of new, wearable technologies - like the Equimetre® device, an innovative product of the Arioneo Company seems to be a proper way to monitor and optimize horse´s training.

Hypothesis: Regularity of the stride is inversely proportional to the stride length and stride frequency. Horses exercising in the "red zone" have a longer recovery time.

Methods: 12 horses were monitored twice with the Equimetre® device while doing speed work over 1700meters. Regularity, stride length, stride frequency, heart rate, speed and recovery time datas have been recorded and analyzed.

Results and conclusion: The regularity of the stride increases with the stride frequency but decreases with the stride length ($p<0, 05$). A horse exercising at more than 80% of its maximum heart rate will have a longer recovery time ($p<0, 05$).

Potential relevance: Regularity of the gallop is an important locomotor parameter, which should be watched for, as irregularity can impair the whole performance. A horse exercised too often near its maximum heart rate or with a prolonged recovery time is prone to fatigue and injury.

HuVetA

ELECTRONIC LICENSE AGREEMENT AND COPYRIGHT DECLARATION*

Name: AIMONETTI EMMA..

Contact information (e-mail): emma.aimonetti@live.fr..

Title of document (to be uploaded): The use of connected devices for the optimization of racing performances in horses, experimental study of different physiological and biomechanical parameters

....

Publication data of document: Budapest, November 14th 2019.................................

Number of files submitted: ....1...

By accepting the present agreement the author or copyright owner grants non-exclusive license to HuVetA over the above mentioned document (including its abstract) to be converted to copy protected PDF format without changing its content, in order to archive, reproduce, and make accessible under the conditions specified below.

The author agrees that HuVetA may store more than one copy (accessible only to HuVetA administrators) of the licensed document exclusively for purposes of secure storage and backup, if necessary.

You state that the submission is your original work, and that you have the right to grant the rights contained in this license. You also state that your submission does not, to the best of your knowledge, infringe upon anyone's copyright. If the document has parts which you are not the copyright owner of, you have to indicate that you have obtained unrestricted permission from the copyright owner to grant the rights required by this Agreement, and that any such third-party owned material is clearly identified and acknowledged within the text of the licensed document.

The copyright owner defines the scope of access to the document stored in HuVetA as follows (**mark the appropriate box with an X**):

- [X] I grant unlimited online access,
- [ ] I grant access only through the intranet (IP range) of the University of Veterinary Medicine,
- [ ] I grant access only on one dedicated computer at the Ferenc Hutÿra Library,
- [ ] I grant unlimited online access only to the bibliographic data and abstract of the document.

Please, define the **in-house accessibility of the document** by marking the below box with an **X**:

- [X]

I grant in-house access (namely, reading the hard copy version of the document) at the Library.

If the preparation of the document to be uploaded was supported or sponsored by a firm or an organization, you also declare that you are entitled to sign the present Agreement concerning the document.

The operators of HuVetA do not assume any legal liability or responsibility towards the author/copyright holder/organizations in case somebody uses the material legally uploaded to HuVetA in a way that is unlawful.

Date: Budapest, 14th….day November.month…2019……..year

Author/copyright owner
signature

HuVetA Magyar Állatorvos-tudományi Archívum – Hungarian Veterinary Archive *is an online veterinary repository operated by the Ferenc Hutÿra Library, Archives and Museum. It is an electronic knowledge base which aims to collect, organize, store documents regarding Hungarian veterinary science and history, and make them searchable and accessible in line with current legal requirements and regulations.*

HuVetA relies on the latest technology in order to provide easy searchability (by search engines, as well) and access to the full text document, whenever possible.
Based on the above, HuVetA aims to:

- *increase awareness of Hungarian veterinary science not only in Hungary, but also internationally;*
- *increase citation numbers of publications authored by Hungarian veterinarians, thus improve the impact factor of Hungarian veterinary journals;*
- *present the knowledge base of the University of Veterinary Medicine Budapest and its partners in a focussed way in order to improve the prestige of the Hungarian veterinary profession, and the competitiveness of the organizations in question;*
- *facilitate professional relations and collaboration;*
- *support open access.*