1. Introduction

Injury to the musculoskeletal system, or the presence of disease, often leads to deficits in motion or functional disorders. Such physical constrictions can impinge greatly upon everyday life and can be detrimental to the career of a professional athlete.

The degree of physical impairment is dependent upon the type of injury sustained, its severity and location.

Injuries to tendons, often caused by overuse, are a major clinical issue in the management of athletes, be they human or equine. Tendons cyclically undergo constant loading and un-loading, often to extremes, and are only capable of minimal elastic elongation, this makes them prone to injury. The most frequently affected tendon in horses, as a consequence of the application of repeated force, is the superficial digital flexor tendon (SDFT). Injury to the tendon as a consequence of strenuous activity can lead to conditions such as tendinitis. Tendinitis may also develop secondary to trauma or peritendinuous injury caused by the application of bandages¹.

Tendons contain little vasculature and as a result blood supply is poor. This is also true of ligaments. This poor blood supply often results in long healing times. As a consequence, management of injuries and rehabilitation requires patience. Resistance to injuries such as tendinitis may be seen to increase with the improvement of the physical conditioning of the horse².

Once tendinitis has occurred within a tendon, it becomes easier for injury to reoccur. Scar tissue can be ‘rigid’ and lack the elastic capability of healthy tendon fibres.

Diagnosis of tendon pathology can often be made with a physical examination (in conjunction with a good patient history). In order to obtain a more detailed
diagnosis, which can then provide information on the type of treatment required, ultrasoundography is used.

Clinically, pathology such as tendinitis produces symptoms of inflammation. Inflammation is a consequence of increased blood flow to injured tissue. This increase in blood flow will increase the temperature of the injured region due to the increase in heat energy being supplied by blood from deep within the body to the afflicted area. As a consequence, inflamed injuries can feel warm to the touch.

Using a technique called thermography, regions of heat build up, and therefore increased temperature, can be visualised.

Thermography is the pictorial representation of surface temperature. Medical thermograms\(^1\) represent the heat emitted from the surface of the skin and as a result, have a wide range of clinical applications, including the evaluation of tendons, ligaments, and distal limbs in horses.

Thermal patterns of uninjured tendons (of opposing limbs) will be bilaterally symmetric. A break from this symmetry, for example the appearance on a thermogram of a ‘hot’ or ‘cold’ spot or region, may be indicative of a region of pathology.

Thermography has the potential to detect regions of injury before symptoms become clinically significant. This ability makes such an imaging modality a useful diagnostic tool, especially when used in conjunction with diagnostic ultrasound and physical examination, in the detection and prevention of debilitating injuries.

Given the large costs involved in owning and maintaining a competitive race horse, the economic consequences associated with lameness justify the effort put into both the quantification and prevention of injury.

\(^1\) The image produced by a thermal imaging camera
2. Theory

2.1. What are Tendons?

Although generally considered to be dull, tendons form an integral part of the musculoskeletal system. Without tendons to connect muscle to bone, human movement, or the movement of any animal be they large or small, would be impossible to emulate.

Tendons consist of bands of dense, fibrous connective tissue. They provide a means of joining muscle to bone and are adapted to respond to the mechanical loads they are constantly subjected to. Thus, tendons vary in size and shape depending upon the morphology and physiology of the bone or muscle to which it is attached. In particular, tendons attaching muscles to limbs, especially during locomotion, are subjected to pro-longed cyclical loads and therefore extended stress levels as compared to when a body is at rest and the loads are static.

In addition to the transmission of mechanical force from a muscle to bone, tendons also act as elastic energy stores. This property is a reflection of the resilient nature of tendons and is an important factor in the evolution of locomotor systems, especially high-speed vertebrate locomotion by ungulate mammals such as horses.

In the case of horses, the tendon of interest is the superficial digital flexor tendon (SDFT). The SDFT can be found running down at the rear of each leg behind the carpus and cannon bones (see Fig.1). The tendon then branches at the fetlock and inserts into the first phalanx, on the distal side, and the second phalanx, on the proximal side (see Fig.2). The tendon is responsible for flexing the carpus, elbow and lower joints.

† Mammals that walk on their toes.
Fig. 1: Skeletal structure of the lower limb of a horse⁴.

Fig. 2: Limb schematic showing the relative positions of the tendons (notice the closeness of the SDFT to the skins surface).
During the act of locomotion the SDFT is stretched each time the foot lands. As a result kinetic energy is stored, transiently, as strain energy within the tendon. As the foot then leaves the ground the strain energy is converted back to kinetic energy as a result of elastic recoil between the foot and the ground.

Despite this elastic recoil, the process of energy transfer is not entirely elastic. As a result of internal viscous damping around 5-10% of the stored energy is released as heat.
2.2. Tendon Structure and Pathology

As previously mentioned in section 1.1, tendons are comprised of dense, fibrous connective tissue. But just what is this fibrous connective tissue and how does it allow for properties seen in tendons?

Tendons are primarily composed of a substance called collagen, the main structural protein for connective tissue found within animals†. Like all complex structures, collagen is comprised of more basic units called tropocollagen.

A tropocollagen molecule is a helical structure approximately 280nm in length. The helical structure itself is comprised of three non-coaxial polypeptide chains. The biochemical nature of the polypeptide chains allows for close packing of the strands. Long collagen fibres are created by the covalent bonding of tropocollagen molecules. A collection of five tropocollagen molecules in cross section forms a microfibril. Microfibrils combined together to form subfibrils. This hierarchical nature continues with subfibrils aggregating together to create fibrils. These fibrils then group to form fibres and fibre bundles. It is within the fibre bundles that the effect of ‘crimping’‡ of the collagen fibres becomes apparent.

Tendons are further made up of fascicles and fascicle bundles (see Fig. 3). The fascicles and fascicle bundles are created through the grouping of fibre bundles. The fascicles are surrounded by a blood and lymphatic vessel containing layer called the endotenon. The endotenon also contains nerves associated with the tendon. The fascicle bundles on the other hand are surrounded by the outermost tendon sheath called the paratenon. In order to reduce the level of friction between the tendon and any surrounding tissue during movement, some tendons are further enclosed by a sheath of synovial fluid.

† The majority of collagen found within the body is known as type I collagen. Other collagen types tend to be tissue specific.
‡ The appearance of a longitudinal waviness in collagen fibre structure.
The primary role of tendon cells (*fibroblasts* and *tenocytes*) is the biosynthesis of collagen. In addition to this, tendon cells are also involved in the maintaining of metabolic balance within the tendon.

In healthy tendons, the rate of collagen metabolism is slow. Tropocollagen molecules are synthesised by fibroblast tendon cells but cross-linking of the molecules to create the collagen fibres is not a quick process. The cross-linking process can take place anywhere from four to sixteen days\(^6\) after molecule synthesis. The formation of collagenous fibres occurs during the next twelve weeks and are at first randomly orientated. As time progresses, the fibres align themselves parallel to applied tensile loads. This continued re-arranging helps to further increase the level of cross-linking between fibres thereby increasing the strength and overall tensile stiffness of the newly formed tendon tissue.

The relatively long periods involved in the formation of new tendon tissue are important issues for the treatment of tendon injuries and give support for the long rehabilitation times.
Depending upon the type of injury sustained, some tendons are capable of ‘self-healing’. Perhaps the most common tendon injury is tendinitis and is synonymous with increased levels of inflammation. However, histopathological data in conjunction with advances in imaging techniques have suggested that tendon pathology may be of a more degenerative nature rather than inflammatory. Degenerative tendon injuries that appear to be devoid of inflammation are termed tendinosis. Due to a limited understanding of tendinopathies, tendinosis may be miss-diagnosed as tendinitis. This can have consequences surrounding any subsequent treatment, rehabilitation and eventual recovery of tendon function.

In the case of tendinitis, pain is associated with inflammation. Treatment protocols therefore focus on the use of anti-inflammatory agents and pain management. Techniques to reduce the degree of early stage inflammation can include ice and therapeutic ultrasound and healing can be augmented provided periods between significant cyclical loading and unloading of the tendon are sufficiently long.

Extended periods of time between activities allow fibroblasts to propagate the repair of any tendon micro-damage. Should an insufficient amount of time be given between bouts of activity then the degree of healing within the tendon will not proceed beyond the inflammatory stage. Such physical restrictions, necessary for the appropriate healing of tendon tissue, can be troublesome should the activity be necessitated through everyday work, or in the case of athletes (both human and equine), training. Conversely, advancing the rate of rehabilitation at too slow a rate can be detrimental to an individual’s ‘productive athletic use’. The formation of scar tissue and peritendinous adhesions during the healing process inevitably result in a potentially weakened tendon. Scar tissue reduces the elastic limit of the healed tendon and subsequently predisposes it to recurrent injury.

As has been mentioned in §1.1, when a tendon undergoes loading and loading, for example, during locomotion, heat is generated. In the case of horses, temperatures as high as 45°C have been recorded within cores of the
SDFT during a gallop exercise\textsuperscript{3}. Temperatures in excess of 40\textdegree{}C that develop within tendon cores as a result of intense exercise can lead to hyperthermia and further degeneration of tendon tissue\textsuperscript{8}. Fibroblasts, when exposed to temperatures of 42\textdegree{}C, begin to show signs of damage\textsuperscript{9}. However, \textit{in vitro} studies of tendon cell responses to temperature variation often involved prolonged exposures, $\geq$ 1 hour\textsuperscript{3,11}, of sustained heat. Since the period of time that a horse would be expected to maintain a high level of locomotion, for example a gallop, would not generally exceed ten minutes, such high temperatures experienced in the tendon core may not therefore necessarily result in immediate cell death.

There exist other factors which may also contribute to tendon degeneration and cell necrosis. During locomotion, the SDFT tendon is constantly being stretched and released. The greatest loads are passed through the SDFT during a gallop\textsuperscript{1}. This cyclical application of stress may cause in an intermittent loss of blood supply to the tendon tissue. The resulting tissue ischemia may then lead to hypoxia\textsuperscript{1} of the tendon cells and inevitably cell death should the hypoxia be sustained.

The risk of developing clinical tendinitis may be heightened when the applied load of the tendon overcomes its resistive strength as a consequence of the additional loading associated with the weight of a rider\textsuperscript{12}. In addition, the risk of SDFT injury to a horse can also increase with increasing race distances, heavier mean body weight, steeplechase experience and sex\textsuperscript{13*}.

A horse believed to be suffering from tendinitis may well present symptoms of inflammation. Inflammation results from an increase of chemicals, released by white blood cells, into the bloodstream. This chemical release also increases blood flow to the area of injury thus causing an appearance of redness upon visual inspection of the skin and an increase in temperature of the region of injury.

\textsuperscript{*} Males were found to have a greater chance of developing a SDFT injury compared to females regardless of racing history\textsuperscript{13*}.
The heat generated, and transmitted to the skin; by increased blood flow during inflammation is dissipated from the body in the form of infrared energy.

Through the use of specialised equipment, such as a *thermal imaging camera* it is possible to visualise this infrared energy.
2.3. An Introduction to the Biochemistry of Tendon Healing

Physiologically, the muscle-tendon and ligament-tendon portions of the SDFT (and the deep digital flexor tendon, DDFT) play important supporting roles in the forelimbs of horses and are necessary to ensure smooth physiological motion and the prevention of joints exceeding their anatomical limits.

Should such limits be exceeded and injury sustained, recovery times can be lengthy and the healed tendon will often lack the mechanical properties of normal, healthy, tissue.

The healing process within a tendon occurs in a number of phases. These phases can overlap and the duration of each is dependent upon the location of injury.

The processes governing the healing of tendons are classically considered to follow two models, intrinsic and extrinsic. Extrinsic healing suggests that the tendon has no internal capability to heal on its own. Instead, the tendon requires the formation of adhesions, the presence of fibroblasts, inflammatory cells and an extratendinous blood supply in order to heal. Intrinsic healing, on the other hand, is instigated by the proliferation of the epitenon and endotenon† and the process is similar to that involved with wound healing.

Initially the response from extrinsic healing processes far outweighs those of the intrinsic response. The result is a rapid ‘filling’ of the injury site with granulation tissue and tissue debris.

With the extrinsic model, the healing process can be broken down into phases. These phases include inflammation, proliferation and re-modelling.

† The epitenon and endotenon are sheath like structures. The endotenon surrounds subfascicular units whilst groupings of approximately 20 subfascicles (a fascicle) are surrounded by the epitenon.
Inflammation occurs almost immediately after injury as a consequence of the release of pro-inflammatory chemicals stimulated by the injury. The presence of macrophages at this stage helps in the recruitment of fibroblasts\textsuperscript{15}.

After the matrix disorganisation of the proliferation phase (a phase dominated by a disorganised tendon tissue matrix and the prominence of fibroblasts), remodelling sees the aligning of the newly formed collagen fibres along the axis of the tendon. This can be instigated by applying a cyclic process of loading and unloading to the tendon as part of a rehabilitation program. During this phase healing can be observed with the naked eye.

The degree of inflammatory response to an injury site is related to the temperature at the site in question. Increases in heat contribute to the synthesis of an enzyme called proMMP\textsuperscript{†} (pro-metalloproteinase). MMPs play an important role in wound healing and in particular matrix degradation. proMMP synthesis is also influenced by a pro-inflammatory cytokine called tumour necrosis factor – α (TNF-α) which can be rapidly released from cells in the presence of heat\textsuperscript{17}. High temperatures, therefore, at a site of injury leads to increased production of pro-inflammatory TNF-α which then leads to greater up-regulation of proMMPs.

The result is an increased inflammatory response and tissue matrix breakdown. With respect to thoroughbred tendons this effect can be significant. During rigorous exercise or racing, the central core of the SDFT sees the most marked increases in temperature\textsuperscript{11}. It is therefore within these cores that tendon degeneration will often begin.

In order to minimise the effects of heat induced tendon degeneration it is beneficiary to cool the afflicted area. The application of cold therapy helps to reduce local circulation by inducing vasoconstriction. A reduction in blood flow can help lessen the effects of haemorrhaging, oedema and the extravasation of inflammatory cells\textsuperscript{18}.

\textsuperscript{†} In particular proMMP-9.
Cold therapy techniques include the use of ice packs, cold water showers or ice-water immersion and cooling boots and are effective up to depths of 1 to 4 cm\textsuperscript{17} from the skin's surface. On average, cold treatments are applied for durations of 15–30 minutes\textsuperscript{19, 20} and are repeated over a period of 24 to 48 hours to aid in the reduction inflammatory effects.

The significant cooling effects of an ice-water bath can be seen in the following figures.

**Fig. 4:** A thermographic image showing the distribution of heat in the hind limbs a horse at rest\textsuperscript{21}.

**Fig. 5:** A thermographic image of the same horse after the application of an ice-water bath to only the left hind limb\textsuperscript{21}.
The applied duration of cold therapy can be extended so long as the temperature can be controlled thus allowing for a continuous cryotherapeutic state\. Conversely, prolonged exposure to temperatures of \(\leq 0^\circ\text{C}\) (ice packs etc) can ultimately be harmful to tissue leading to blistering and burns.

\(^\dagger\) Achieving a controlled temperature is often difficult with applications such as hosing.
2.4. Infrared Radiation and Thermography

Infrared is a form of radiation that comprises part of what is known as the electromagnetic spectrum.

The light that we see also forms part of this spectrum; however, it is both of a different wavelength and frequency and forms, what is known as, the ‘visible region’ of the electromagnetic spectrum. Unlike light, infrared radiation is not visually perceptible instead it is experienced as heat.

All objects within the universe emit infrared radiation so long as their temperature remains above absolute zero$. The amount of infrared radiation emitted by an object is dependent upon the object’s temperature.

This amount of emitted radiation, that is, the degree of thermal emission, is usually described in terms of it’s relation to what is known as a black body.

A black body is defined as that object which is capable of totally absorbing all incident radiation regardless of its wavelength. Such an idealised object, would theoretically, therefore, reflect no radiation and appear perfectly black.

Since the concept of a perfect black body is a theoretical construct, it is used as a standard with which the radiation characteristics of other, real life and non-perfect, media are compared.

The emission of radiation from a black body is given by Planck’s law,

\[
\frac{dR(\lambda, T)}{d\lambda} = \frac{2\pi h c^2 \lambda^{-5}}{\exp(hc/\lambda kT) - 1}
\]  

$(1)$

$^\dagger$ Absolute zero, or zero Kelvin, is defined as -273.15°C
where \( \frac{dR(\lambda, T)}{d\lambda} \) is the power emitted per unit area per unit wavelength, \( h \) and \( k \) are Planck’s and Boltzmann’s constants respectively and \( c \) is the speed of light (see Appendix 1 for a table of values). \( T \) is the absolute temperature of the black body in degrees Kelvin.

The rate at which an object emits radiation (and therefore energy) is proportional to the fourth power of the object’s absolute temperature and area. This relationship is described by the Stefan-Boltzmann law,

\[
P = e \sigma A T^4
\]

\( P \) is the power radiated by the object, \( \sigma \) is Stefan’s constant (see Appendix 1) and \( e \) is the emissivity of the object. Emissivity is a value that ranges from 0 to 1 depending upon the surface composition of a material and is defined as the ratio of the energy radiated by an object to the energy radiated by a black body at the same temperature. A black body would have an emissivity equal to 1.

Should an object emit more radiation that it absorbs then it will cool whilst its surroundings will warm up (by absorbing the emitted radiation). Conversely, if an object absorbs more than it emits then it will warm up, while this time its surroundings will cool.

If an object emits and absorbs radiation, both to and from its surroundings, at the same rate then both the object and its surroundings are at the same temperature and are said to be in thermal equilibrium. This is a precursor to the zeroth law of thermodynamics:

“If two objects are in thermal equilibrium with a third, then they are in thermal equilibrium with each other.”
Wavelengths incorporating infrared radiation range from around 1 µm to 20 µm. Despite this range, not all of the wavelengths are useful. Many are absorbed by atmospheric constituents such as carbon dioxide (CO₂) and water (H₂O). Thus absorption of infrared energy can be influenced by atmospheric conditions such as humidity and fog as well as smoke. However, environmental problems such as these can be compensated for technologically through the use of atmospheric correction filters.

When considering the imaging of any emitted infrared radiation it is necessary to anticipate the temperature of the object under examination. Objects with temperatures that emit infrared radiation at wavelengths around 1µm are not terribly useful for imaging purposes. Infrared energies within this wavelength range are often used for applications such as short range remote controls.

The mid and long-wave bands of the infrared portion of the electromagnetic spectrum tend to be the most useful for imaging purposes. These wavelength bands range from 3-5 µm to 8-14 µm and suffer least from atmospheric absorption.

The use of infrared radiation for imaging purposes is called thermography, and is widely termed ‘thermal imaging’. Thermography has widespread application ranging from the defence and semiconductor industries through to veterinary medicine.

What makes thermography such a valuable tool is that it is able to detect small changes in temperature with good resolution and without being placed in contact with the object. This has significant advantages when being used as a diagnostic instrument, especially on non-human subjects who may oppose being touched with imaging equipment and may invariably therefore need to be sedated. Sedation is, of course, not without its risks or logistical problems.

Due to their small and portable size and relative low cost compared to other diagnostic imaging devices, modern thermal imaging cameras have found a practical use in the field of equine injury diagnosis.
As described in §1.2, various pathologies are associated with increased levels of heat generation. Thermography is able to visualise regions of increased temperature and display them graphically on an image, termed a thermogram, which can then be interpreted by the user. Areas of maximal thermal radiance, such as regions of increased blood flow, are often shown as bright colours, or “hot spots”, (white, red, orange) on a thermogram. Increases in blood flow to a particular area may be attributable to inflammation or injury. Conversely, “cold spots”, represented by colours such as green, blue, purple and black, may be indicative of circulatory problems. An example thermogram is shown in the following image.

![Thermogram of hands](image)

**Fig. 6: A standard thermogram of both the left and right hand. Notice the degree of thermal symmetry produced by healthy tissue.**

The detected emission of heat from a body can be affected by several factors including cellular metabolism, degree of vasculature and amount of adipose tissue which can have an insulating effect. In addition, environmental conditions, to which the object under examination is subjected to, need to remain, where possible, constant. In particular, the higher the ambient environmental temperature the less heat is dispersed from the body as radiation. Instead, the effect of evaporation becomes dominant.
The rate of heat loss from a body may alter according to the ‘nature and intensity of the biological phenomenon’\textsuperscript{24} in question and vary with the size and type of tissue involved. It is important to note that since thermography only detects the heat emitted from the surface of a body; it is possible that different phenomena may be present at the same time, masking each others thermal signature. Thermography at present, therefore, does not reveal anatomical structure but instead is able to give information on the “status” of tissue at a given time.

When used in conjunction with a clinical exam, the diagnostic ability of thermography can provide ‘highly effective results’\textsuperscript{18} when pin-pointing areas of suspicion.
3. Literature Review

Like all professional athletes, racing thoroughbreds suffer the career shortening scourge of musculoskeletal injury. Such injuries, in particular to the tendons, may prove to be asymptomatic thus allowing for the continuation of training, often with detrimental results.

It is now possible to identify regions of potential pathology well in advance of the onset of any observable clinical problems as the following studies will demonstrate.

One of the more common areas of injury suffered by horses is tendinitis of the superficial digital flexor tendon. The superficial digital flexor tendon (SDFT) has a complex role. It not only flexes the digit but also stores energy for locomotion (Smith et al, 2000). It was also shown that tendons have a limited ability to adapt and the continuation of exercise leads to increased micro-trauma which ultimately results in tissue degradation (Smith et al 2000). As a consequence of their function, primary disorders of tendons (tendinopathies) tend to be common, especially in athletes, both human and equine.

Tendinitis is often used to describe the chronic pain associated with a symptomatic tendon injury. The use of the term tendinitis implies a pathological process indicative of inflammation. However, according to Rees et al (2006), tendon pathology may be, depending upon the injury, devoid of any inflammation. This is an important consideration when attempting to thermally image a tendon previously diagnosed with tendinitis. A reduction in, or complete lack of, inflammation may result in a thermal signature lower than might be expected. The most common descriptions of tendon pathology include tendinosis (a degenerative condition without accompanying inflammation, pain is caused by micro tears in the connective tissue), the aforementioned tendinitis and a collective term, tendinopathy, which can be used to describe either of the previous two. Such varying classifications play an important role in any subsequent injury management. Depending on the
nature of the injury, it may take upwards of six months for the majority of healing within a tendon (or ligament) to take place (Gillis 1997). During this period (6-8 months, Gillis, 1997) and beyond, it is necessary for the patient to rest and undergo rehabilitation. Worsening of the injury can occur should patient activity be advanced too quickly, whilst prolonging the rehabilitation may lead to a loss of productive athletic capability. In the case of race horses, either of these two scenarios can prove costly.

In horses, tendinitis often reoccurs when training is resumed before the site of injury has healed. Heat, which is a contributing factor to tendon pathology, is generated as a consequence of the constant extension and contraction of the tendon during exercise. Temperatures as high as 45°C (Yamasaki, 2001) can be generated within tendon cores if a horse gallops. Such high temperatures can have a significant impact on the survival rate of tendon fibroblasts.

A means of determining the temperature at the core of tendons, in particular the superficial digital flexor tendon, in horses was devised by Yamasaki et al (2001). The study saw two horses (male and female) undergo a regime of both track running and resting. Temperature measurements of the (approximate) SDFT centre were made using a 'needle type sensor'. In order to do this it was necessary to anesthetise the horse. Whilst such a procedure would provide more direct measurements of the SDFT temperature, the method itself undoubtedly places the subject under some degree of stress and the logistical implications involved in the anesthetising of such a large animal are considerable.

In the case of the horses at rest, temperature measurements were made 5 minutes after sedation†. Temperature measurements were made of the SDFT in addition to other areas of interest. An equine leg cooling sheet was also applied a total of 7 minutes after the horse was first administered the anesthetic.

† Measurements began after 5 minutes for one horse whilst they took place after 3 minutes for the second.
Measurements found that the surface temperature of the skin tended to rise for greater than 12 minutes on the treated limb. No other appreciable changes were noticeable. This was true of both horses.

In order to exercise the horses, Yamasaki et al had the subjects run one lap of a dirt track. Both horses completed the lap in less than 4 minutes‡. Horse 1 was anesthetised 56 seconds after running and measurements were made 3 minutes after sedation.

Ideally, it would be more appropriate to assess tendon temperatures in a way that is non-invasive for the subject under examination. One such, non-invasive, technique currently employed in the study and identification of musculoskeletal injuries is thermography.

Research into musculoskeletal injuries has shown that thermography can 'predict joint and tendon problems two weeks before they become clinically apparent' (T A. Turner et al, 1986). Thermography is used medically to detect heat radiated from the surface of skin. This heat can be generated by local circulation in a region of interest, metabolism or surface contours. Heat is seen to be a cardinal sign of inflammation (Turner et al, 2001).

In the study carried out by Turner et al (2001), thermography was used as a means to determine injury in thoroughbreds by how well it correlated with the findings of a treating veterinarian. The study was carried out inside of a barn to eliminate effects from direct sunlight and drafts. The thermographic images were then evaluated to identify areas of abnormality and these areas were compared and correlated to a veterinarian’s findings.

Results showed that there was only an insignificant increase (from 4.6 to 4.8) in thermographically detected abnormalities between horses that were walked or galloped 48 hours prior to examination. However, a significant increase (5.3 abnormalities) was noticed in horses that had undergone speed work prior to imaging with the largest detection of abnormalities (5.7) occurring in horses

‡ 3 min 24 sec and 3 min 9 sec for horses 1 and 2 respectively.
that had taken part in racing 72 hours beforehand.

The areas of abnormalities were divided into particular regions of interest including shins, fetlocks and tendons. Of all thermograms produced, only 18% demonstrated tendon abnormalities. However, of those horses that did show signs of tendon abnormality, 89% went on to develop clinical problems. The study demonstrated that there was an “excellent agreement between thermography and soreness” in those horses studied and was able to detect signs of inflammation before symptoms became apparent.

Turner et al’s study also suggested that thermographic examination should take place at least 2 hours after maximal exercise and that special consideration of the feet be taken since they were found to remain ‘hot’ up to 24 hours after a gallop exercise.

The study concluded that thermography could be used to better determine racing intervals for horses. However, these ‘intervals’ were not elaborated upon.

Further studies to determine the efficacy of thermal imaging in the diagnosis of diseased conditions was carried out by Embaby et al (2001) using subjects admitted to veterinary clinics in Giza, Egypt. The study by Embaby et al found that thermography was the ‘most sensitive objective imaging available’, especially in the case of equine back pain and was able to detect areas of inflammation before it became clinically apparent. In addition to its viability as a diagnostic tool, thermal imaging also had the capability to monitor the progression of recovery from injury.

Of the 45 horses studied, 15 presented symptoms of acute lameness. The degree of lameness was found to increase in intensity after exercise. Examination of the afflicted area with ultrasound demonstrated an absence or reduction in tendon fibre patterns. This pathology was further investigated with thermography. Using a colour coordinated output display ‘hot spots’ indicating areas of inflammation were identified and compared with an unaffected limb.
Once afflicted limbs were identified, treatment was administered and monitored with the thermal imaging camera. Results showed a decrease in thermal gradients.

The study carried out by Embaby et al. (2002) concluded that thermography was capable of locating areas of injured tissue but could not give any information concerning any morphological changes. As with Turner’s study (Turner et al., 2001), it was suggested that thermography could well be used to provide information pertaining to the recovery time of an injured horse.

A means of determining the time taken for surface temperatures of equine thoracic and pelvic limbs to return to pre-exercise levels after high speed treadmill exercise was carried out by Simon et al. (2006).

All horses used had been conditioned to use of a treadmill and the surrounding ambient temperature was recorded. The exercise regime consisted of a walk, slow trot, trot and a slow gallop, all for duration of 5 minutes. After the gallop, the trot, slow trot and walking exercises were then performed for 3 minutes each as a warm down.

Thermal images of the desired regions were obtained immediately after halting of the exercise and again after 5, 15, 45 and 60 minutes, as well as 6 hours after cessation. The thermographic images were compared to ‘baseline’ images obtained 3 days prior to exercise.

From the data obtained, there appeared to be “no significant difference in surface temperature between thermograms obtained before exercise and those obtained ≥ 45 minutes after exercise was stopped”.

The study concluded that, in horses, the thermographic images obtained were not influenced by the heat generated through exercise ≥ 45 minutes after the exercise had been stopped.
4. Method

Having addressed the issues of heat induced pathology and the benefits of cooling an afflicted area in §2.2 and §2.3 and their supportive studies (§3), the next step, to be addressed by this study, is to quantify the effectiveness of the cooling treatment.

It is known that under certain conditions core temperatures of the SDFT can reach 45ºC (page 8) and that sustained temperatures of ≥40ºC (page 8) can have degenerative effects on tendon cells, ultimately leading to pathologies such as tendinitis. The aim is, therefore, to reduce the temperature of the tendon as quickly as possible after intense heat inducing activities such as training or racing. Ordinarily, after strenuous activity, a horse may well be hosed down with cold water in order to provide cooling, sometimes for upwards of 20 minutes\textsuperscript{25}, but is this really an effective measure to prevent, or at least delay, the onset of a pathological process?

To investigate this, a method was devised to investigate the heating effects in the limbs of horses in response to exercise and to determine the effectiveness of the aforementioned cooling procedures. It was hoped this study could address the following hypotheses:

1. How quickly can the application of cold treatment reduce the temperature of the SDFT to levels whereby tendon degeneration can be minimised?

2. Of the widely used cooling methods, which is the most effective, if any? That is, how quickly does the tendon temperature increase back to degenerative levels after cold treatment?

The effectiveness of the cooling techniques will be compared through their ability to reduce the temperature of the SDFT to within, or below, a predefined range after exposure to a heat inducing regime. This regime will take the form of a brief exercise program.
In order to address this investigation the following protocol was devised:

**Materials to be used:**


2. Use of stable facilities and treadmill equipment (courtesy of Buckholt Park, Tendon Works, Kent)

3. Several thoroughbred horses (courtesy of Buckholt Park, Tendon Works, Kent). One horse with no diagnosed pathology was to be used as a control whilst all others under investigation would have been diagnosed with tendinopathy pre-thermographic examination.

4. Digital thermometer.

**Method(s):**

1. Initial imaging of horses at rest having undergone no prior exercise. These initial baseline images will provide proof of concept to demonstrate thermographically the temperature variation between healthy and potentially inflamed tendon tissue.

2. Initiation of a short exercise routine. This will be performed in accordance with (or a variation of) that defined by Simon *et al* (2006, page 24)²⁶.

The routine will be conducted upon a treadmill and will include the following steps:

- Walk (5mins)
- Slow trot (5mins)
- Trot (5mins)
- Slow Gallop (5mins)
- Trot (3mins)
- Slow trot (3mins)
- Walk (3mins)

(Or a variation of the above, for example, 10 minute walk and then a 5 minute trot with no gallop. The degree and duration of exercise is dependent upon the nature of the injury carried by the horse under examination. It is not the aim of the exercise regime to cause further injury).

3. Imaging will commence immediately after halting of the exercise (at time, \( t = 0 \) minutes) and again after \( t = 5, 10, 15, 20, 25, 30, 35 \) and 40 minutes. Measurements of \( t \geq 45 \) mins will not be taken in light of the findings of Simon et al (2006). Images will be taken of both the left and right limbs of either the hind or fore limbs, depending upon where the pathology is localised, for comparative purposes.

Conclusion of step 3 will provide information on the natural cooling of the tendon, that is, the distal limb area, without cold treatment intervention.

4. Repeat step 2. Upon halting of the exercise image immediately the distal limbs (\( t = 0 \) minutes) and then apply cold treatment.

**Equine cooling boots:**

- Apply boot to affected limb for 5 minutes then remove and re-image.
- Apply boot to affected limb for 10 minutes then remove and re-image.

**Hosing with Water:**
• Hose with cold water the affected limb for 1 minute then remove and re-image.
• Hose with cold water the affected limb for 2 minutes then remove and re-image.
• Hose with cold water the affected limb for 3 minutes then remove and re-image.

**Controls:**

1. Horse not suffering with lameness to follow the same exercise and cooling regime.

2. Perform all imaging:
   - In the same location undercover and away from drafts and direct sunlight.
   - At the same ambient environmental temperature, where possible. Temperature readings will be taken prior to the initiation of the exercise regime.
   - With the same camera control settings.
   - With approximately the same object-camera distance.

**Data Interpretation:**

1. Thermograms captured by the thermal imaging camera to be transferred to a PC. Using the accompanying software package (*ThermaCAM™ Researcher*, FLIR Systems), regions of interest\(^\dagger\) (ROI) can be defined and average temperatures calculated.

2. Data will be displayed on temperature versus time plots.

\(^\dagger\) Areas on the thermogram pertaining to the SDFT will be corroborated by an on-site specialist.
5. Results

Due to changes in circumstances regarding the acquisition of data, the method proposed in §4 was modified such that it was now acting as a pilot study. The following results reflect these changes.

In total four horses were examined, all of which were diagnosed as having forelimb tendinopathy. The horses were imaged prior to, during and after exercise. The exercise regime consisted of two 10 minute walking sessions on a treadmill. The treadmill remained flat first 10 minutes while it was increased to a 5% incline for the second 10 minute session.

Imaging, whilst the horse was on the treadmill, was performed in 30 second intervals. This allowed for both the collection of numerous images and the ability to observe the changing heat patterns of the limbs as the regime progressed. The images themselves were captured to a laptop computer connected to the thermal imaging camera. The camera was also connected to a digital video recorder that allowed for playback of the exercise and imaging cycles.

After the completion of the 20 minute walking program, each horse was walked outside for approximately 30 seconds and then brought back into the examination barn where they were again imaged. The focus of the examination was on the rear of the forelimbs (given the anatomical location of the SDFT, see §2.1, pages 3-4). This is in contrast to the images taken during exercise which, as a consequence of the practical arrangements of the camera-treadmill setup, were of the front.

The following is a breakdown of the data obtained for each of the horses examined.

**Horse 1: ‘Achilles’ – Pathology in the right-hand forelimb:**
The following images are of the forelimbs of Achilles as seen from the front with the camera positioned approximately two metres from the end of the treadmill. The image was taken prior to the initiation of exercise (effectively, $t = 0$).

![Thermographic image of horse 1 at rest prior to exercise.](image)

**Fig. 7:** Thermographic image of horse 1 at rest prior to exercise.

The following is the same image but displayed using a different colour palette.

![Thermographic image of horse 1 (as in Fig. 7) but using the ‘rain’ colour palette.](image)

**Fig. 8:** Thermographic image of horse 1 (as in Fig. 7) but using the ‘rain’ colour palette.

It is apparent to see the marked asymmetrical distribution of heat between the
two forelimbs. The right forelimb is considerably cooler than the left prior to exercise.

This difference can be seen more vividly from the following analysis of the image depicted in Fig. 8.

![Thermographic image of two forelimbs with temperature scale](image)

Fig. 9: Line insertion from the approximately the centre of the knee to approximately the position of the fetlock joint.

The resulting temperature profile is as follows:

- The ThermoCAM™ Researcher software allows the insertion of lines along which temperature profiles of a ROI can be calculated and displayed. The lines are of an arbitrary length but correspond to an equivalent anatomical distance.
Fig. 10: Screenshot from ThermaCAM™ Researcher – Forelimbs of horse 1.

Line 1 represents the right leg and line 2 the left. From a visual inspection of the above, the left leg is clearly warmer than the right. The left leg had an average temperature of 24.4 ± 0.9 ºC along the pre-defined length compared to 21.5 ± 0.9 ºC for the right.

The following image was captured after the completion of two 10 minute walking sessions on the treadmill.
Fig. 11: Thermographic image of the rear of the forelimbs of horse 1 post exercise.

As with before, lines along which temperature profiles could be calculated were placed along the rear of the limbs. This is shown in Fig. 12.

Fig. 12: Thermographic image of the rear of the forelimbs of horse 1 as previously shown in Fig. 11. Lines along which temperature profiles are calculated run from just below the knee to approximately the Fetlock joint.

The resulting profile is as follows.
Fig. 13: Screenshot from ThermaCAM™ Researcher - Rear of forelimbs of horse 1.

In this profile line 1 (LI01) depicts the left leg and line 2 (LI02) the right. The average temperature along the length of line 1 is 26.0 ± 0.3 °C. For line 2 the average temperature is 26.5 ± 0.5 °C.

Horse 2: ‘Jacob’ – Pathology in the right-hand forelimb (obvious signs of swelling):

The following images depict the forelimbs of Jacob prior to exercise with inclusion of the temperature profile.
Fig. 14: Thermographic image of the forelimbs of horse 2 prior to exercise.

As with the forelimbs of horse 1, the temperature profiles were made from approx. the middle of the knee to the fetlock joint.

Fig. 15: Screenshot from ThermaCAM™ Researcher - Forelimbs of horse 2.
Line 1 (LI01) corresponds to the right limb and line 2 (LI02) the left. The average temperature along the length of line 1 was 26.7 ± 0.5 °C whilst line 2 had an average of 27.3 ± 0.3 °C.

As with horse 1, horse 2 was also imaged after completion of the exercise routine.

![Thermographic of the rear of the forelimbs of horse 2 after the completion of the exercise routine.](image)

Fig. 16: Thermographic of the rear of the forelimbs of horse 2 after the completion of the exercise routine.

The temperature profile for the rear forelimbs of horse 2 is as follows.

Notice the ‘stripy’ patterns running across the rear of the limbs. This is scarring due the effect of a technique called ‘firing’ (see §6, page 45).
As before, line 1 (LI01) corresponds to the left hand side and line 2 (LI02) the right hand side. The average temperature along line 1 is $28.1 \pm 0.6 \, ^\circ C$ and $28.2 \pm 1.6 \, ^\circ C$ for line 2.

**Horse 3: ‘Sonny’ – Pathology in the left-hand forelimb (signs of swelling and inflammation):**

With horse 3 the procedure of imaging the front forelimbs prior exercise was changed to imaging of the rear of the forelimbs prior to exercise. The result is shown in Fig. 18.
Fig. 18: Thermographic image of the rear of the forelimb of horse 3 taken prior to exercise. Notice the significant difference in temperature of the two limbs.

Fig. 19: Screenshot from ThermaCAM™ Researcher – Temperature profile for the rear of the forelimbs of horse 3 prior to exercise.
From Fig. 19, the average temperatures given by the left (line 1 – LIO1) and right (line 2 – LI02) limbs are $30.0 \pm 0.5^\circ C$ and $24.4 \pm 0.5^\circ C$ respectively.

Upon completion of the two 10 minute exercise sessions the rear of the forelimbs were again imaged.

**Fig. 20: Thermographic image of the rear of the forelimbs of horse 3 post exercise.**

The temperature profile generated by the line positioning as shown in Fig. 20 is shown on the following page.
Fig. 21: Screenshot from ThermaCAM™ Researcher – Temperature profile for the rear of the forelimbs of horse 3 post exercise.

The line assignment is the same as that described by figures 19 and 20. The average temperature along the length of line 1 was $29.9 \pm 0.3$ °C and $25.2 \pm 0.5$ °C for line 2.

Horse 4: ‘Roy’ – Pathology in the left-hand forelimb:

As with horse 3 (‘Sonny’), the initial image take of the horse at rest was of the rear of the forelimbs.
Fig. 22: Thermographic image of the rear of the forelimbs of horse 4 at rest prior to exercise.

Fig. 23: Screenshot from ThermaCAM™ Researcher – Horse 4.
The average temperature along line 1 (LI01) corresponding to the left limb was $29.5 \pm 0.7 \, ^\circ C$ and for the right limb (line 2, LI02) the average was $28.4 \pm 1.5 \, ^\circ C$.

As before, the rears of the forelimbs were again imaged after the completion of the exercise regime. The resulting images and temperature profile are shown below.

![Thermographic image of the rear of the forelimbs of horse 4 post exercise.](image)

Fig. 24: Thermographic image of the rear of the forelimbs of horse 4 post exercise.

It should be noted from the above image the degree of heat distribution symmetry that exists between the two limbs.

The temperature profile and averages are shown on the following page.
Fig. 25: Screenshot from ThermaCAM™ Researcher – Temperature profile for the rear of the forelimbs of horse 4 post exercise.

From the temperature profile, the average temperature along the length of line 1 (left hand limb) was $31.6 \pm 0.6 \, ^\circ\text{C}$ and for line 2 (right hand limb) the average was $31.1 \pm 1.1 \, ^\circ\text{C}$. 
6. Discussion

In total this study looked at four horses all of which presented signs or symptoms of varying grades of tendon pathology.

All the horses were of a varying age and size but the same sex, male. Although four horses is by no means a representative sample, this observation lends support to the idea that sex may be a factor associated with the risk of incurring a tendon related injury\textsuperscript{13}.

As is evident from §5, the thermograms for each horse are unique. That is, there is no standardised way of viewing different subjects. Each subject may present to the camera different physical and physiological characteristics that can affect what the camera ‘sees’. Thus camera settings for one horse may need to be adjusted for another. This is an example of the subjective nature of thermography, much in the same way that the diagnostic capability of ultrasound is dependent upon the ability of each individual operator to interpret the images.

The results of §5, and in particular the thermographic images of Achilles, demonstrate how variable tendinopathies can be. Should a horse pull up lame how often, after a superficial examination, would the causal factor be attributed to pathology such as tendinitis? Tendinitis, by its very nature, is associated with irritation and inflammation of the tendon and with inflammation there follows an increase in heat of the afflicted area (see §2.3, page 12). The treatment for such a condition would inevitably involve the application of cold therapy to lower the core temperature of the tendon and to minimise the inflammatory response (see page 13). However, the data obtained for Achilles poses an interesting problem. The injured limb was between 1.1 °C and 2.9 °C cooler than the coolest average temperature of the healthy limb (23.5 °C\textsuperscript{†}). Even after the completion of the exercise regime the temperature of the

\textsuperscript{†} Found simply by subtracting the error (the standard deviation) from the average (see §5, page 32, for the relevant values).
healthy limb still only remained within two standard deviations of the injured limb.

During the exercise routine the injured limb was slow to heat up as is evident from the thermogram in Fig. 12 (page 33) where the right limb still has areas of low heat radiation. Even more prominent is the difference in radiated heat from both limbs prior to initiation of the exercise routine (Fig. 9, page 31). The coolness of the distal regions of right limb is indicative of a lack of blood flow and may therefore indicate problems with the vasculature of the right limb. Should the blood supply to the lower limb be restricted in some way then the chances of an injury occurring are higher since tissues are being starved of the necessary blood constituents. Similarly, should an injury occur then healing times may be lengthened for the same reasons. Therefore, a tendon injury may well be a secondary effect to another primary problem which is not so easily diagnosed 'in the field'.

As described in §2.3 (pages 12-14), tendon injuries are often dealt with using cold therapy techniques. In the case of Achilles, where the limb was already cold, such additional cooling may well have no further effect and prove to be little more than a waste of time.

In comparison, horse 2, ‘Jacob’, was also suffering from a right-hand forelimb tendon injury yet the average temperatures of both the healthy and injured limbs remained relatively close both before and after exercise. In addition, the thermographic images of Jacob both prior to initiating the exercise routine and after (Fig 14, page 35 and Fig. 16, page 36) also displayed a good degree of symmetry. It is also interesting to note the visual effect of the ‘firing’ process evident on the rear of the forelimbs (Fig. 16). Firing, also termed ‘pin firing’, is something of an antiquated procedure that involves the application of a heated iron to the skin surface in order to produce local inflammation of superficial structures. The aim is to produce counter irritation and to improve the healing process. There is little evidence to suggest the effectiveness of this process instead it believed to cause more pain and lengthen training times\textsuperscript{27} yet in an industry steeped in tradition it is still occasionally employed.
As with Jacob, the thermographic images of horse 4, ‘Roy’, also demonstrated a degree of symmetry and again the temperature differences between the injured and uninjured limb were small, though the injured limb was, on average, the warmer of the two both before and after exercise.

Another interesting comparison can be made between horse 3, ‘Sonny’, and horse 1, ‘Achilles’. Both Sonny and Achilles offered a similar clinical presentation, yet their thermographic examinations produced quite different results. Examination of Achilles prior exercise revealed an injured limb that was cooler than the healthy limb, yet examination of Sonny prior to exercise revealed a limb that was considerably warmer, between 4.6 and 5.6 °C, relative to the same area on the opposite, healthy limb (Fig. 18, page 38). The injured limb also remained warmer than the healthy limb after the completion of the exercise regime though the amount of heat radiated did not appear to increase over that of the limb at rest. The average recorded temperature along the pre-defined line shown in Fig. 20 (page 39) was marginally lower, but within the realms of error, than that of the limb at rest (29.9 ± 0.3 °C and 30.0 ± 0.5 °C respectively). The increased radiance of heat from the injured limb over that of the healthy limb may be attributable to inflammation (Turner et al, 2001, page 22). From the theory of sections §2.2, §2.3 and §2.4, increasing the loading through and work done by the tendon should increase the inflammatory effect thus further increasing the temperature of the limb, yet this was not directly observed. However, there are several reasons as to why the observation may disagree with the theory. They include:

1. The location of the line along which the temperature profile is calculated. Positioning the line within a region of interest and then matching that location on another object is highly subjective. As a consequence of the camera angle and relative orientations of the limbs it can become impossible to accurately mark regions that correspond to anatomically the same point. This could potentially be overcome by capturing multiple images from a range of pre-defined angles about the object being examined. However, logistically this may prove difficult to execute.
2. Duration and nature of exercise. This pilot study only looked at the effect of walking on the temperature change of the distal limb regions. In order to generate more appreciable radiative differences between limbs it may be necessary to increase the loading of the tendon by increasing the work rate of the horse. The exercise program created by Simon et al (2006) included a trotting session (slow trot followed by a trot, total time of 10 minutes) followed by a 5 minute slow gallop. It has been shown that the symptoms of acute lameness tend to increase in intensity after exercise (Embaby et al, 2001).

3. Nature of the pathology. Given the lack of concise understanding surrounding tendinopathies what may be regarded as one particular type of pathology may in fact be another. If pre-diagnosed tendon pathology turns out to be devoid of inflammation, or at least devoid of significant levels of inflammation, then that particular pathology’s thermal signature will be lower than expected (Rees et al, 2006). In other words, what may have started out as tendinitis, a pathology associated with inflammation, upon thermographic examination could turn out to be more representative of degenerative pathology, i.e. tendinosis (page 8).

4. Time of examination. All the horses were imaged almost immediately after the cessation of exercise (each horse was walked outside for approximately 30 seconds before being brought back into the examination barn). However, the expected inflammatory response form the injured tendon may not have been immediate. For future study this problem can be addressed by taking images of the limbs at set time intervals for a pre-defined time period after the completion of the exercise program (c.f. Simon et al, 2006, page 24).
7. Conclusion

In summary, this pilot study has shown that:

- Thermography is a capable, if subjective, diagnostic tool. Each individual examination ought to be taken on its own merits and direct comparisons between images of different subjects ought to be made cautiously.

- Different horses presenting the same symptoms or clinical history may well produce different results upon thermographic examination.

- Thermography can be used as a means to identify additional regions of abnormality that may go unnoticed in another examination (page 45).

- Degenerative pathology (tendinosis) may play a larger role in equine lameness. Of the horses studied two did not show, thermographically, signs of significant inflammation. Temperatures between healthy and injured limbs tended to be of the same order both before and after exercise.

- There may be a need to address the ideas and procedures behind the current management of tendon injuries. Application of cold therapy to injured limbs that are already cold may prove to be a waste of both time and resources and may ultimately have no therapeutic value. Unnecessary application of cooling boots and ice-water baths may actually be detrimental to the rehabilitation of the horse by causing further vasoconstriction of the blood vessels supplying the tendons.
8. Evaluation

Due to time limitations this study was unable to address the hypotheses declared in §5 (page 25). However, as a precursor to further study in this field, this pilot study has demonstrated to a reasonable level the efficacy of thermography and its potential as a diagnostic tool.

This study has demonstrated, through thermographic investigation, the ability to highlight regions of abnormality not evident through a simple visual or tactile inspection as may be performed by an owner or trainer. Being able to detect regions of the body that are unusually cold, in addition to the more well established ‘hot’ regions associated with inflammation, may well lead, upon further investigation, to the detection of additional pathology associated with the circulatory system.

The results obtained in this study have also highlighted a number of short comings attributed to thermographic examinations. Thermography is very much an object specific technique. Unlike CT or MRI, where the properties of individual anatomical structures are standardised thereby producing images of the same form regardless of the patient, thermograms, like ultrasound, are much more subjective. Changing a setting can alter an image’s appearance and subsequently an operator’s opinion of what is being shown.

Future study in this area could involve:

- Detailed thermographic analysis of heat distribution in the limbs of horses having undergone more rigorous exercise programs. This could be extended to examining horses after mock ‘races’ on varying track surfaces (the shock absorbing effects will be different to that of a treadmill surface).
• Application of additional image processing techniques, i.e. creation of an algorithm that will define a region of interest corresponding to an anatomical location (for example, the SDFT).

• Investigation into the cooling ability of the various cold therapy techniques (as outlined in §4). This could lead to the development of guidelines regarding the duration of application of each method and their effectiveness in cooling limbs to levels where the likelihood of tendon degeneration is minimised.
Appendix 1

The following table defines those constants described in Planck’s law as stated in §1.3.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck’s, $h$</td>
<td>$6.626 \times 10^{-34} Js$</td>
</tr>
<tr>
<td>Boltzmann, $k$</td>
<td>$1.381 \times 10^{-23} JK^{-1}$</td>
</tr>
<tr>
<td>Speed of light, $c$</td>
<td>$2.998 \times 10^8 ms^{-1}$</td>
</tr>
<tr>
<td>Stefan’s, $\sigma$</td>
<td>$5.670 \times 10^{-8} Wm^{-2} K^{-4}$</td>
</tr>
</tbody>
</table>
References


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