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**Computed tomographic evaluation of bone density in the distal third metacarpal bone in
31 non-lame showjumpers**

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List of abbreviations

BMD – bone mineral density

BVTV – bone volume fraction

CT – computed tomography

GAG – glycosaminoglycan

HU – Hounsfield unit

McIII – third metacarpal bone

MRI – magnetic resonance imaging

1. Introduction

Extensive research exists on pathologies in the fetlock joint of Thoroughbred racehorses, including studies on pathogenesis and diagnostic imaging findings [1–3]. There are several descriptions of magnetic resonance (MRI) abnormalities in the fetlock in both race- and sports horses [2–6]. The importance of osseous lesions in the fetlocks of non-racing sports horses has been recognised [5,7,8], but there are limited publications on fan-beam CT findings in the fetlock of showjumpers and no objective CT findings have been reported. This study aimed to contribute to improved understanding of adaptive and pathological changes in the metacarpophalangeal joint in sports horses, by describing the pattern and extent of bone density in the distal aspect of the third metacarpal bone (McIII) of non-lame showjumpers using objective computed tomographic measurements.

2. Literature Review

2.1 Functional anatomy of the metacarpophalangeal region

The front fetlock (metacarpophalangeal) joint is composed of the distal aspect of McIII, the proximal phalanx and the medial and lateral proximal sesamoid bones. The basis of the McIII is located proximally [9]. The shaft (body) of McIII is convex dorsally, while the palmar aspect is almost flat. The McIII has a transverse oval cross-section [9,10]. The body is followed by its caput at the distal end of the bone, which consists of the medial and lateral condyles with the sagittal ridge in between. They form an articular surface, which opposes the articular surface of the base of the proximal phalanx [9]. On the palmar aspect, the metacarpal condyles articulate with the dorsal articular surface of the proximal sesamoid bones [10]. The palmar abaxial aspects of proximal sesamoid bones form a groove, in which the flexor tendons run distally [10].

The suspensory apparatus prevents the fetlock joint from overextension and is composed of the suspensory ligament, the proximal sesamoid bones and sesamoidean ligaments [10]. Both flexor tendons, inclusively their accessory (check) ligaments, aid the suspensory apparatus in stabilising the fetlock joint [10,11]. The muscle bodies originate proximal to the carpus and their tendinous extensions insert on the phalanges, contributing to a “pendulum-like” effect [11,12]. Distal to the fetlock, the superficial digital flexor tendon divides into two branches that insert on the middle scutum. The deep digital flexor tendon

inserts on the flexor surface of the distal phalanx [9]. Between the palmar abaxial surfaces of the proximal sesamoid bones a deep fascia thickens and forms the palmar annular ligament, which contributes to holding the flexor tendons in position when the fetlock is extended [10]. The suspensory ligament originates on the proximal palmar aspect of the McIII with additional fibers originated from the palmar aspect of the third carpal bone and the axial aspect of the fourth metacarpal bone. In the distal third of the metacarpal region, it splits into two branches, which insert on the proximal sesamoid bones. From each branch, an extensor branch extends towards the dorsal surface of the proximal phalanx and join the common extensor tendon [9,10]. On the dorsal surface, the common digital extensor tendon runs along the McIII and inserts on the extensor process of the distal phalanx [10]. The lateral digital extensor tendon runs lateral to the common digital extensor tendon and inserts on the dorsolateral aspect of the proximal phalanx [9]. The fetlock joint is supported by collateral ligaments between the McIII and the proximal phalanx medially and laterally and by the collateral sesamoidean ligament between the proximal sesamoid bones and the medial and lateral aspect of McIII [10].

2.2 Biomechanics of the fetlock

The combination of linear and rotational movements created by internal and external forces contribute to equine locomotion. The basic repeated unit of movement is a single stride [12]. A stride consists of two phases: the weightbearing stance phase and the non-weightbearing swing phase [11,12]. During ground contact and load absorption, hyperextension of the fetlock joint is limited by contraction of the flexor muscles and their tendinous elongations and the support of the suspensory ligament. In the fully weightbearing mid-stance phase, eccentric contraction of the flexor muscles prevents the limb of collapsing and support the fetlock joint in hyperextension [11]. The dorsal aspect of both the lateral and medial metacarpal condyles are in direct contact with the proximal phalanx during hyperextension of the fetlock, while the palmar aspect of the condyles and the proximal sesamoid bones absorb the weight-bearing forces directly [9]. Concentric contraction of the flexor muscles initiates the caudal propulsion phase by releasing stored energy from muscles, tendons and ligaments, shifting the horse's body forward [11]. In summary, the fetlock region and its suspensory apparatus absorb energy in early stance phase, which is released in late stance [11,13].

The swing phase consist of two main movements: retraction and protraction. The limb acts like a pendulum. To initiate retraction, all joints flex by concentric contraction during the caudal phase of a swing phase, before extending again in the cranial phase to prepare for landing and the following stride [11,12].

The accumulation and release of elastic strain energy is considered particularly important in equine locomotion, as it helps to minimize energy-intensive muscular activity [14]. The storage of strain energy relies on accumulation of relatively high forces within the superficial digital flexor tendon, deep digital flexor tendon and the suspensory ligament. These forces generated by the tendons spanning the fetlock joint play a crucial role in the joint's contact forces, even at moderate speed gaits, including trot [14]. Although the joint contact forces in galloping horses have not been measured, the high occurrence of fatal metacarpophalangeal joint injuries in racehorses strongly implies that this joint endures significant loads at higher speeds [14].

In equine locomotion, different gaits are characterised by a specific pattern of limb coordination in repeating sequences. A symmetrical gait is defined by almost identical kinematics and kinetics on each forelimb or hindlimb. The walk is a symmetrical gait and is defined as a slow-paced, regular, four-beat gait [12]. At walk, elastic energy storage and release across the fetlock region is smaller than in trot [13]. The trot is a medium-speed, regular, two-beat gait. The trot is considered the horse's preferred gait for continuous movement, since forward movement and the required energy expenditure are well balanced [13]. Asymmetrical gaits such as gallop or canter are defined by different kinematics and kinetics for each limb [12]. The gallop is a rapid, four-beat, leaping gait, whereas canter is a controlled, three-beat, leaping gait. Higher speed leads to decreased stance duration and increased stride length for each limb [12]. In canter there is always at least one limb with ground contact, while in gallop there is a flight phase [12].

2.2.1 Biomechanics of jumping

To initiate a jump, intrinsic and extrinsic muscles must perform synergistically. During the jump, horizontal movement is transformed into vertical movement like a pole-vault [11]. Approaching take-off, the head, neck and the trunk drop while the forelimbs are loaded. Promptly after ground contact, a maximal joint extension following eccentric contraction is crucial for muscle activation and vertical propulsion. Take-off is initiated by pushing and protracting of the forelimbs and elevation of the trunk between the limbs, due to eccentric

contraction of the muscular girdle, followed by forceful concentric contraction and fast extending of joint angles [11].

During the flight phase, the forelimbs undergo two main movements: 1) flexion of the joints and horizontalisation of the shoulder during upward movement and 2) extension of the joints during the descending phase. The fetlock, the proximal and the distal interphalangeal joints extend subsequently, followed by the proximal limb [11]. The impact of the vertical landing of the forelimbs and the subsequent drop of the body mass are one of the most demanding phases on the limbs and therefore contribute to a risk for injury [11,15].

Jumping is an asymmetrical activity, in which the forelimbs are loaded differently [16]. There are in vitro studies on loading of various parts of the metacarpophalangeal joint [17–19], but to our knowledge, the loading pattern of the McIII of showjumpers have not been investigated specifically.

Forces and their distribution on the joint are influenced by how the foot makes ground contact and are counteracted by the muscular girdle and regulated by flexion of joints. During take-off, the contact limb (the trailing forelimb) is contralateral to the leading limb of the last canter stride [11]. The trailing limb is used to elevate the center of mass of the body [20]. Absorption of forces begins immediately after the contact limb hits the ground and both forelimbs are exposed to ground reaction forces after landing, which are higher than the ground reaction force at take-off [20,21]. The leading limb encounters loading over a longer period, absorbing horizontal and vertical forces. Therefore, the collective load absorption is greater in this limb. The contact limb experiences a greater peak vertical force and almost no horizontal velocity [15]. The duration of ground contact at landing decreases more in the contact limb than in the leading limb, which is even more pronounced when jumping higher fences [13]. During landing, the trailing contact limb is exposed to the highest strains and ground reaction forces [8,13]. In general, ground reaction force amplitudes increase when jumping higher fences [13]. Furthermore, the contact limb experiences higher flexor tendon loading than the leading limb. Ground reaction forces are positive during the whole stance phase of the contact limb, while the leading limb encounters positive ground reaction forces only during the first part of the stance phase [9].

The jumping technique of a horse influences load absorption of the forelimbs [13]. Horses with an appropriate jumping technique can take a low jump with minimal effort while barely changing the canter pace, which reflects in similar ground reaction force at canter, take-off and landing. By increasing the fences' height, forces increase sharply [13]. Loads can be

similar in horses using inferior jumping technique over a smaller jump to superiorly performing horses over a higher jump [13].

The contact area between the McIII and the proximal phalanx increases due to the vertical movement applied to the joint during the landing phase of a jump. This shifts the highest pressure to the dorsal aspect of the McIII [22].

According to Wolff's law, bone changes its structure in response to loading [14]. The McIII is exposed to external and static stresses, caused by pulling of tendons and ligaments, as well as ground reaction forces during locomotion [23]. The "cannon-bone" construction of the metacarpal diaphysis allows to achieve maximum performance with a minimum of material. Despite extensive savings in material, however, the bone has performance reserves that not only enable it to cope with its static stresses, but also help to withstand the dynamic forces that act in them with varying intensity [9].

Earlier in vitro research assessing pressure distribution, documented a predominantly axial compression of McIII [10,16]. More recent in vivo studies have shown that load distribution deviates from the axis [16,17]. Strain gauges provide an effective and reliable method to measure tissue behavior under physiologic load [4]. Davies et al. used rosette strain gauges on the dorsal distal cortex of McIII to measure the surface strain under controlled exercise conditions, horses were exercised on a treadmill with increasing speeds from 2-16.5 m/s [24]. The study demonstrated that most of the loading on the dorsal McIII resulted in compression, based on the peak principal strains. By increasing speed, a rotation of the neutral axis was observed, which moved the area of peak strain from medial to the dorsomedial cortex of the McIII [17].

2.3 Bone mineralisation

A bone is composed of inorganic and organic substances. Elasticity and flexibility are characteristics of the organic matrix. A fully developed bone generally consists of approximately one third organic ossein and two thirds of inorganic material, in which calcium phosphate predominates with 85%, followed by calcium carbonate (approximately 10%), magnesium phosphate and calcium fluoride [9]. Hydroxyapatite is the main component of the bone mineral content, which contributes to strength and rigidity. Bone mass, geometry and tissue material properties influence bone strength [12,25]. Bone strength at a specific anatomical site is affected by the amount and proportion of trabecular and cortical bone [25].

The mineralisation process is regulated in the bone matrix by phosphoprotein kinases and alkaline phosphatase [25]. Dentin matrix protein 1 and bone sialoprotein (nucleators) promote mineralisation. Passive mineralisation is regulated by the stimulating function of vitamin D [25].

Bone modelling and remodeling continue throughout life. Bone remodeling is defined as bone renewal, which includes bone resorption and bone forming, to provide bone strength, mineral homeostasis and to avoid accumulation of microdamage [25]. Bone modeling is defined as bone formation, which includes adaptive changes in the overall bone shape during growth and aging, without prior resorption [12,25–27].

The focal bone remodeling balance is regulated by orchestrated osteoclast-osteoblast activity. The information transfer between the cell sets, in control of remodeling of the basic multicellular unit, is called focal coupling. Osteoclast receptors and regulatory factors are coupled with osteoblasts at all differentiation stages to synthesize bone matrix and subsequently induce bone mineralisation [27,28]. Osteoblasts then differentiate into osteocytes, which manage adaptive remodeling by balancing osteoblast and osteoclast function. Osteocytes make up 90-95% of the cells in the mineralised matrix of bone and are ideally disseminated to percept external mechanical loads [21].

Increased load on the bone leads to increased mineral density, which allows the bone to withstand higher demands. If the bone is exposed to recurrent physical stresses exceeding its reparative capacity, microdamage occurs and the physiologic processes can become pathological, leading to precursor lesions that may progress to fatigue fractures [2].

Regular strenuous training that is too high in intensity for the bone's ability to respond, can lead to reduced remodeling. Circulating bone markers of bone resorption, absence of resorption surfaces in the trabecular bone and a reduced porosity in the dorsal cortex of distal McIII are present in training horses [29]. The ratio of the volume of bone to the total volume (bone volume fraction), was found to be higher in horses with an advanced racing career [29]. Increased bone volume fraction leads to the loss of normal trabecular bone architecture, which is associated with the fracture site of metacarpal condylar fractures [29].

Fatigued bone is replaced by adaptive remodeling, which is an effective method of fracture prevention. However, stiffness and yield strength are temporarily reduced during the process of remodeling, which is increased in regions of high strain [29].

As remodeling is reduced by repetitive strains, adaptive modelling becomes the main mechanism for maintenance of bone strength. Whitton et al. propose this mechanism as the reason for increased density in the subchondral bone of the distal McIII of Thoroughbred

racehorses [29]. Structural changes of bones have been linked to the start of exercise in a horse's career [21]. A marked increase in bone volume fraction occurs within eight weeks after training start of a young racehorse [29]. Bone mineral density (BMD) increases with training and decreases during inactivity. Intense training without a preceding transition period increases the incidence of bone fractures [30]. Modelling may prolong the fatigue life of a bone but cannot prevent fractures [29].

2.4 Constituents of bone structure

The diaphysis mostly consists of cortical bone, whereas metaphysis and epiphysis are composed of trabecular bone [4,18]. The subchondral bone is adjacent to the articular cartilage. Structure and function of subchondral bone varies by region. The subchondral bone is denser and more solid close the calcified cartilage and transitions into a more porous form closer to the trabecular bone [26].

2.4.1 Characteristics of trabecular bone

Hydroxyapatite, collagen and water are the main components of trabecular bone. The calcium content, tissue density and ash fraction are lower than in cortical bone, which consequently leads to a higher proportion of water [28]. Remodeling occurs more in trabecular than in cortical bone, resulting in a lower mineralisation ratio, since newly formed bone is less mineralised [28]. Normal trabecular bone structure is lost at sites with an increased bone volume fraction, which makes these regions prone to fractures [29].

With different structural and physiological features, the trabecular bone is adaptable and less resistant, whereas cortical bone is solid [21,30,31]. The trabecular bone has a multi-level, spongy and porous structure with a higher matrix turnover rate, leading to a higher proportion of young, less mineralised bone [12,28]. The trabecular bone lattice is built of trabecular struts and plates, creating a framework for the intertrabecularly located bone marrow. This construction allows optimised mechanical load transfer from the articular surface to the cortical bone [28]. Trabecular bone is capable of reacting to local forces directly [30]. Therefore, bone volume fraction increases in trabecular bone in response to repetitive loading [29].

A positive linear correlation between a lower bone mineral density in trabecular bone and failure strength has been shown [30]. An increased mineralisation leads to increased stiffness of bones, shifting the absorbed forces to the cartilage [32,33]. The applied load and

subsequently the adaption of bone tissue, may be partially reflected by differences in strength within the regions and along the longitudinal axis of the McIII [31].

2.4.2 Characteristics of cortical bone

In horses, due to the functional stress the limb is exposed to, the already very strong cortical (compact) bone of McIII is even more developed in its structure dorsally and medially [9,10]. The cortical bone surrounds the marrow space as a dense and solid material. The structural units forming cortical and trabecular bone are called osteons [25]. Cortical osteons are known as Haversian systems. These systems have a cylindrical structure and create a branching network throughout the cortical bone. Cortical bone usually has a porosity of about 5%, though this may change depending on the balance between active Haversian canals and inactive cortical osteons [25]. The outer surface of cortical bone is surrounded by a tightly attached fibrous connective tissue sheath, the periosteum. The inner surface of cortical bone, trabecular bone and blood vessel canals (Volkman's canals) is covered by the membranous endosteum [25].

2.4.3 Characteristics of the subchondral bone

The subchondral bone consists of the subchondral bone plate and subchondral trabeculae. The subchondral bone trabeculae and the articular cartilage are connected through the subchondral bone plate, a thin layer of calcified cartilage [26]. The penetrable structure of the latter ensures generous vascularisation and innervation.

Some characteristics of the subchondral bone depend on the anatomical region and on the thickness of the subchondral bone plate. The depth ranges between 10 μm and 3 mm [26]. In thinner areas, a small number of Haversian canals and trabeculae can be found; in thicker layers a network of osteons is present. One of the main functions of subchondral bone is to absorb mechanical loads and respond quickly to these forces. The flexibility of trabecular bone complements the subchondral bone by aiding in energy dissipation throughout all layers of the joint [26]. It also provides elasticity and support. All layers must be balanced and facilitate each other's function. Rigidity is provided through hydroxyapatite crystals, the inorganic component of subchondral bone. The organic components, type I collagen and proteoglycans, along with water, contribute to the tissue's adaptability. Because of its composition and its plentiful vascularization, subchondral bone is highly adaptable to both acute and chronic stresses [26].

2.5 Lesions in the distal third metacarpal bone

2.5.1 Cartilage

Repair abilities of the articular cartilage are limited due to the lack of vessels and nerves and only one cell type (chondrocytes) present in this tissue. Thinning and fibrillation are common degenerative cartilage abnormalities in equine athletes [1]. Wear lines, associated with impaired mechanical function, can occur across the articular cartilage of the condyles of McIII [5].

The sagittal ridge is susceptible to articular cartilage fibrillation or ulceration, because of changes in biomechanical properties of the articular cartilage, collagen fibers and subchondral bone [1]. Palmar osteochondral disease is a common abnormality in the palmar aspect of the metacarpal condyles of Thoroughbred racehorses [1]. The location of lesions corresponds to the articulation with the proximal sesamoid bones in fetlock hyperextension and the coherent load absorption during training and racing [1].

Hitting a jump, getting a show jump pole tangled between forelimbs, falling or stumbling are traumatic events which may lead to traumatic cartilage damage in the fetlock joint [34]. Cartilage loss is usually present in the dorsal aspect of the metacarpal condyles. Furthermore, osseus fragmentation of the dorsoproximal medial or lateral aspect of the proximal phalanx can also occur. These osseus fragments might damage the opposing articular cartilage and lead to secondary osteoarthritis [34].

2.5.3 Bone

Fractures involving the metacarpal condyles are one of the most prevalent fracture types and occur most commonly in racehorses, elite endurance horses and occasionally in event horses [34]. Preexisting subchondral bone sclerosis, microfractures and erosion are pathological features, which influence and accelerate the development of condylar stress fractures, mostly located on the distal palmar aspect of McIII [3,34]. The cumulation of bone stress injuries is possible when repair mechanisms of bone (remodeling) are overwhelmed due to repetitive stresses [2].

Bone stress injuries can be classified into three different stages: stress reaction, stress fracture and complete fracture [2]. Stress reaction is defined as prefailure event at cellular level and the first warning sign of a forming bone stress injury, manifesting as a bone marrow lesion. An incomplete fracture line defines a stress fracture at a macroscopic level. The

propagation of an incomplete fracture due to reoccurring stresses may lead to a complete fracture, which might be catastrophic. Bone stress injuries can be subclassified as low or high-risk injuries [2]. Displaced lateral condyle fractures are a common fatal injury of racehorses, whereas non-displaced lateral fractures have a better prognosis [34]. The fracture originates from the palmar aspect of the lateral condyle and propagates proximally towards the lateral cortex of McIII [1,34]. Medial condylar fractures are more prone to progressing in a spiraling way proximally up to the diaphysis [34].

The detection of bone marrow lesions might be helpful for early identification of a fatigue induced bone injury [2]. In a low-field MRI study of non-racing sports horses, bone marrow lesions were commonly seen in the dorsal aspect of the sagittal ridge and the medial condyle of McIII [22]. It must be noted that these lesions were also seen in non-lame limbs. Likewise, Dyson et al. documented subchondral bone lesions mostly in the distal aspect of the metacarpal condyle of sports horses [7]. The location of bone marrow lesions in Thoroughbred racehorses is mostly the palmar aspect of the distal McIII [22]. Biomechanical differences in load distribution while racing or jumping may explain the different location of lesions [22]. De Guio et al. studied the occurrence of bone marrow lesions in the distal metacarpal condyles of sports- and pleasure horses by using low-field MRI [22]. The distribution of bone marrow lesions of jumping horses were not different to horses whose training does not include jumping (e.g., dressage horses) [22]. It was proposed that the dorsal aspect of the condyles and the sagittal ridge of McIII are loaded during the landing phase of a jump and also after the suspension phase of extended canter in dressage horses. Both result in higher vertical forces on the dorsal surface, which may explain the location of the lesions. Additionally, the biomechanical aspects of frequent turns in both dressage and showjumping may be relevant [22].

The sagittal ridge of McIII is a common site of osteochondrosis, which is a consequence of focal disturbances during endochondral ossification [34]. These lesions frequently occur bilaterally [35]. In the initial stages of the disease, lesions are only detectable by microscopic examination [35]. As the condition progresses it can become detectable radiographically as radiolucent lesions [5,35]. In more advanced stages, cartilage flaps may separate from the parent bone, leading to osteochondrosis dissecans [35].

Traumatic chip fractures may occur in older horses on the distal aspect of the sagittal ridge, similar to the typical site of osteochondrosis or in showjumpers who strike an obstacle with the fetlock in a flexed position [34]. Chip fractures may also originate from the proximal aspect of the proximal phalanx [34].

Osseous cyst like lesions most commonly occur in the medial condyle on the weightbearing surface of McIII and can be a manifestation of osteochondrosis. Usually, yearlings and young horses are diagnosed with this lesion [34].

2.5.4 Subchondral bone microdamage

Most previous research on subchondral bone microdamage and injury focuses on Thoroughbred racehorses [1,4,7,32,36,37]. The importance of subchondral bone damage in non-racing sports horses has been recognized, however published information is limited and most have focused on the proximal phalanx [7,8,38].

The extent of microdamage that causes clinical signs has not been specified. Pain related to damaged subchondral bone can be caused by increased intraosseous pressure, hypertension, instability or impingement of the periosteum, ligaments or joint capsule [26]. Subchondral bone sclerosis is commonly seen in association with osteoarthritis and is related to subchondral microdamage [33,36].

Riggs et al. showed on 12 two-year-old Thoroughbreds that bone density increases in horses exposed to high intensity work, manifesting as higher density in the palmar aspect of the distal condyles and the metaphysis of McIII on CT images, digital radiography and backscattered electron microscopy [32].

Pearce et al. demonstrated that in racehorses the bone volume fraction, bone mineral density and stiffness values were higher on the palmar subchondral bone than on the dorsal site of McIII [39]. Furthermore, differences in superficial and deep subchondral bone were highlighted, e.g., as a higher bone volume fraction and lower bone mineral density in superficial layers than in the deep subchondral bone [39]. An increase in bone volume fraction increases the possibility of microcracks in the subchondral bone. The palmar McIII site stood out by showing hardly any difference in bone volume fraction between layers. All other sites showed increased stiffness in deeper layers of the bone, regardless of variations in bone density and damage levels. Nonetheless, the stiffness gradient increased due to modeling generally, and there was no sign of microdamage [39]. A considerable new bone formation leads to a stiff bone structure within the condyles and concentration of strain in the parasagittal grooves, which subsequently extends to the subchondral bone [17,32,36,37]. In gallop, the palmar aspect of distal McIII experiences shear forces at the contact site with the sesamoid bones, on top of compressive forces. Consequently, bone volume fraction, bone mineral density and stiffness values are increased in racehorses in the palmar condyles [39].

This leads to increased density of the subchondral bone and the potential of focal subchondral bone failure [32,33]. In gallop, the superficial bone layer must withstand the highest forces, resulting in greater energy absorption [39]. Riggs et al. highlighted that in racehorses the sagittal ridge of McIII is an exemption and appeared to be significantly less dense, as it is not directly loaded during functional weight bearing [32].

Lucent regions visible on the distal palmar aspect of McIII on lateromedial radiographs are indications of advanced subchondral bone injury [34]. These injuries can be detected in earlier stages by using advanced imaging techniques. If training intensity is reduced, the bone can remodel and the level of microdamage decreases [8,36]. Presumably regeneration itself is not sufficient for the more extensive microdamage at the palmar site of the McIII for an active racehorse [39].

The schedule of many competing showjumpers requires the horse to recover quickly and to accomplish challenging courses with varying time gaps in between [7]. Cyclic high loading can negatively influence the repair process, resulting in bone fatigue and cumulative damage [1]. Previous research has shown that the resting time allowed for many regularly competing showjumpers is not sufficient for bone regeneration [37].

In a publication preceding this study, Nagy and Dyson described densification of the trabecular bone as the most common subjective CT and MRI finding in the front fetlock of non-lame showjumpers. Densification was most often seen on the dorsal and palmar aspects of the medial condyle and the palmar aspect of the lateral condyle [5]. No objective image analysis was performed.

2.6 Diagnostic imaging modalities

Diagnostic imaging is performed once lameness is localized to a region by clinical examination, gait assessment and diagnostic analgesia [26]. Radiographic examination is the first diagnostic imaging tool to evaluate osseous structures [7]. For radiographic examination of the fetlock, standard projections include dorsopalmar, lateromedial, flexed lateromedial and dorso45lateral-palmaromedial and dorso45medial-lateromedial oblique views [34]. Proximodistally tilted oblique views and flexed dorsopalmar views might add additional information on the distal aspect of McIII [26,34]. Although these special radiographic projections can improve visualisation of the palmar aspect of McIII, superimposition of other osseous structures remains the main limitation of radiographic assessment [3].

Ultrasonographic examination is used to identify tendon, ligament and other soft tissue injuries in the fetlock region. Ultrasonographic waves do not penetrate bone, but ultrasonography can be valuable to assess the surface of the bone and articular cartilage and evaluate osseous fragments in the dorsal aspect of the fetlock joint [34]. However, ultrasonographic access to most part of the fetlock joint itself is limited.

Nuclear scintigraphy, MRI and CT are more sensitive to detect early subchondral bone abnormalities than radiography [26]. Nuclear scintigraphy is commonly used to detect injuries of the fetlock joint in racehorses [4] and has been useful in identifying subchondral and trabecular bone lesions in sport horses [34]. Scintigraphy primarily reflects bone turnover by showing differences in radiopharmaceutical uptake [3,7]. As resolution of scintigraphic images is limited, further imaging modalities may be necessary to assess anatomical structures in greater detail [3]. Flexed lateral and dorsopalmar scintigraphic images can help differentiation between increased radiopharmaceutical uptake in the palmar aspect of McIII and the proximal sesamoid bones [34].

For a long period of time, MRI was the one of the most advanced imaging modalities to diagnose subchondral bone abnormalities in the horse [6]. As an increasing number of CT systems allowing examination of the limbs in a standing position is available, CT is increasingly used in lameness investigations [6,26,40]. Computed tomography produces detailed cross-sectional images and offers great spatial resolution, which is advantageous in identifying subtle osseous pathologies [41]. However, in clinical settings CT cannot detect fluid in bone [2]. Currently early diagnosis of bone marrow lesions, a precursor pathology of a high-risk bone stress injury, is only achievable by using MRI and/or scintigraphy [2].

Motion artefacts remain a limitation of standing CT examinations, but motion correction softwares help to obtain good quality images [40,41]. Fan-beam CT has been shown to be superior to cone-beam CT; it provides greater details on osseous structures and better soft tissue differentiation [41]. Lin et al. compared the imaging modalities cone-beam CT, fan-beam CT and low-field MRI for the detection of palmar osteochondral disease in Thoroughbred racehorses and revealed the CT was more sensitive than MRI. However, MRI allowed more detailed evaluation of the severity and pathological status of the lesion by different signal intensity alteration [42].

2.6.1 Imaging non-lame horses in full work

Fetlock region pain is one of the main causes of lameness in racehorses and non-racing sports horses [8,22]. The concurrent use of MRI and CT has increased over time, but earlier descriptive research focused mainly on soft tissue MRI findings surrounding the fetlock joint of lame Thoroughbred racehorses [40,42,43].

The knowledge of potential incidental findings on MRI or CT images is essential for a correct diagnosis of imaging studies of lame horses [5]. Recently, MRI, CT and radiographic findings in the fetlock joint of non-lame Thoroughbred yearlings have been published [44]. These results are likely not applicable to older non-racing sports horses [5]. The preceding publication of this longitudinal project is the first one to document subjective comparative fan-beam CT, low-field MRI and radiographic findings in the fetlock joint of 31 non-lame showjumpers in full work [5]. Authors described a range of abnormalities that had been previously associated with lameness. Densification of the trabecular bone in both the dorsal and palmar aspect of the medial condyle and the palmar aspect of the lateral condyle of McIII was the most common finding in >80% of limbs [5]. MRI and CT were both able to detect the densification, but densification in the palmar aspect of the condyles could be identified more frequently when using CT acquisitions than MRI. No objective assessment was performed. Previously, densification in the sagittal ridge and both metacarpal condyles have been associated with fetlock region pain [7]. Cone-shaped densification was seen on MRI images only and was a common finding in the sagittal ridge of non-lame Thoroughbred yearlings [44]. Focal subchondral bone lesions in the dorsoproximal aspect of the medial condyle were associated with lameness in an MRI study [45], but bilateral presence of a similar lesion might reflect a developmental abnormality or a rare form of osteochondrosis [5]. Subclinical osteoarthritis can be associated with mild periarticular modelling, commonly seen in MRI and CT images, but not in radiographs [8].

To our knowledge, no previous studies performed objective analysis of fan-beam CT images on the fetlock joint of non-lame sports horses in full work.

3. Aims and hypotheses

The overall aim of the study was to describe the densification pattern in the distal aspect of McIII in non-lame showjumpers by assessing the mean Hounsfield Unit (HU) values in 10 regions of interest. Furthermore, we wished to compare mean HU values between different measurement sites (dorsal vs. palmar, medial vs. lateral and left vs right forelimb) and to investigate any potential association between mean HU values and age and competition level.

Based on previous literature and the published subjective findings on our study population [5], we hypothesised that the greatest mean HU would be seen in the dorsal aspect of the medial condyle and that there would be a positive association between mean HU and age and competition level.

4. Materials and methods

The current project was part of a longitudinal study, in which sequential imaging of the front fetlocks of 31 non-lame Warmblood show jumper sport horses was performed [5]. Horses were in full training and competition and had no history of or significant clinical findings related to metacarpophalangeal joint disease. Horses underwent clinical assessment and subjective and objective lameness evaluation. Three age and level categories were set: in Group 1, horses were 5-6 years old and competed at ≥ 110 cm; in Group 2, horses were 7-9 years old, competing at ≥ 120 cm; in Group 3, horses were >9 years old, competing at ≥ 130 cm.

The study protocol was approved by the Ethical and Animal Welfare Committee of the University of Veterinary Medicine Budapest and by the Government Office of Pest County (PE/EA/1051-7/2021) on 23 September 2021.

Computed tomographic examination of both metacarpophalangeal joint regions was performed using a fan-beam CT system with a platform accustomed to allow examination in a standing position (Qalibra CT System, Vet-DICon, Zossen, Germany), with a 16-detector multislice helical scanner and a bore diameter of 90 cm. The scanning window extended from the distal third of the metacarpal region to the level of the proximal interphalangeal joint, with the following acquisition settings: 135 kV and 350 ms, 0.5 mm slice thickness, 320 mm field of view and 0.5 s rotation time. Images were analysed in a medical image viewing software (JiveX DICOM viewer, Version 5.2, Visus Health IT GmbH, Bochum, Germany, using multiplanar reconstruction with a 0.3 mm extension voxel size.

Reference images for measurements were obtained using a standardised method. First, a midsagittal plane image was reconstructed, transecting the most dorsal and palmar point of the sagittal ridge in a transverse image. Subsequently, the plane of the midsagittal reconstruction was set along the longitudinal axis of the McIII in frontal images. The most proximal dorsal and palmar edges of the sagittal ridge were connected, and the 2/3 of its width was marked, which the frontal reconstruction was aligned to. This frontal reconstruction was used to set up the location of the sagittal reference images, on which measurements were performed (Figure 1A). These locations included the sagittal ridge, the medial and lateral parasagittal grooves and the medial and lateral condyles. The latter images were set at halfway between the most medial and lateral aspects of the condyles. The most proximal dorsal and palmar aspects of the sagittal ridge, the parasagittal grooves and the

condyles, respectively, were connected. The region distal to this line was divided midway into dorsal and palmar regions of interests, by drawing a line to the most distal part of the sagittal ridge (Figure 1B). The mean HU was measured in 10 regions of interest: the dorsal and palmar aspects of the medial and lateral condyles, medial and lateral parasagittal grooves and the sagittal ridge. To assess repeatability, all measurements were obtained three times on five limbs.

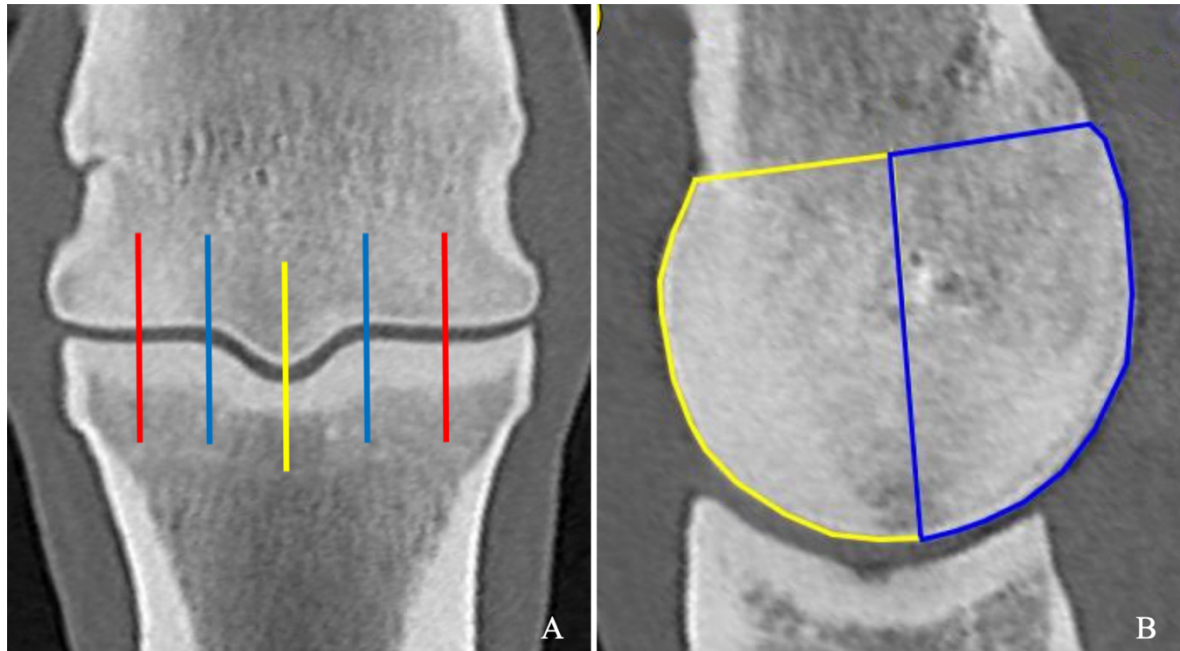


Figure 1. Representation of the measurement set-up. A: Measurement sites: Sagittal ridge (yellow); parasagittal ridges (blue); condyles (red). B: Connection of the most proximal dorsal and palmar aspect, divided midway into dorsal (yellow) and palmar (blue) region of interests

Descriptive data analyses were performed using the statistic software IBM SPSS Statistics, Version 29.0.2.0 (20). Based on the normal distribution of the data, paired t-tests were used to compare mean HU in between dorsal and palmar and medial and lateral regions of interest and between the same regions in the left and right forelimb. Univariable logistic regression was performed to investigate associations between regions with the highest mean HU and age and competition level. Statistical significance was set at $p \leq 0.05$.

5. Results

5.1 Horses

There were 14 mares, 12 geldings and 5 stallions. Eight horses were aged 5-6 years old and were competing at 110-115 cm. Nine horses, aged 7-9, were competing at 120-125 cm. Fourteen horses were >9 years old and were competing at a level ≥ 30 cm. The mean bodyweight of the horses was 570.0 ± 45.5 kg, and the mean height was 168.4 ± 4.4 cm.

5.2 Hounsfield Unit measurements

Repeatability of the measurements were confirmed with a coefficient of variance of <2% percent for all measurements. The mean HU was greater in the dorsal than the palmar aspect at all measurement sites, ($p < 0.001$) (Figures 2 and 3). A comparison between medial and lateral sides revealed that the mean HU was greater in the medial dorsal aspect than in the lateral dorsal aspect ($p < 0.001$) (Figure 4).

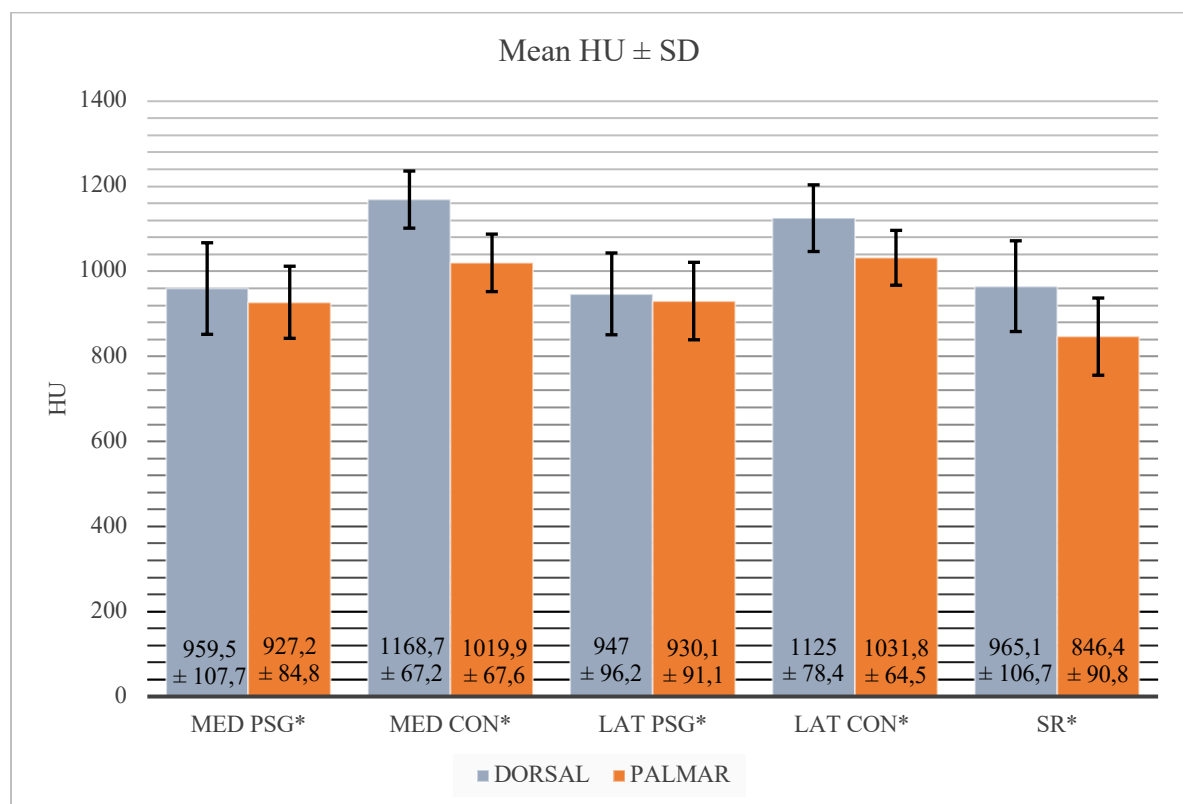


Figure 2. Mean Hounsfield Unit (HU) and $\pm$ standard deviation (SD) in the dorsal and palmar aspects of the distal third metacarpal bone. MED PSG – medial parasagittal groove; MED CON – medial condyle; LAT PSG – lateral parasagittal groove; LAT CON – lateral condyle; SR – sagittal ridge; *significance <0.001

In the palmar aspect of the condyles and parasagittal grooves, there was greater mean HU laterally than medially, while dorsally the mean HU was greater in the medial aspect ($p<0.001$) (Figures 4, 5).

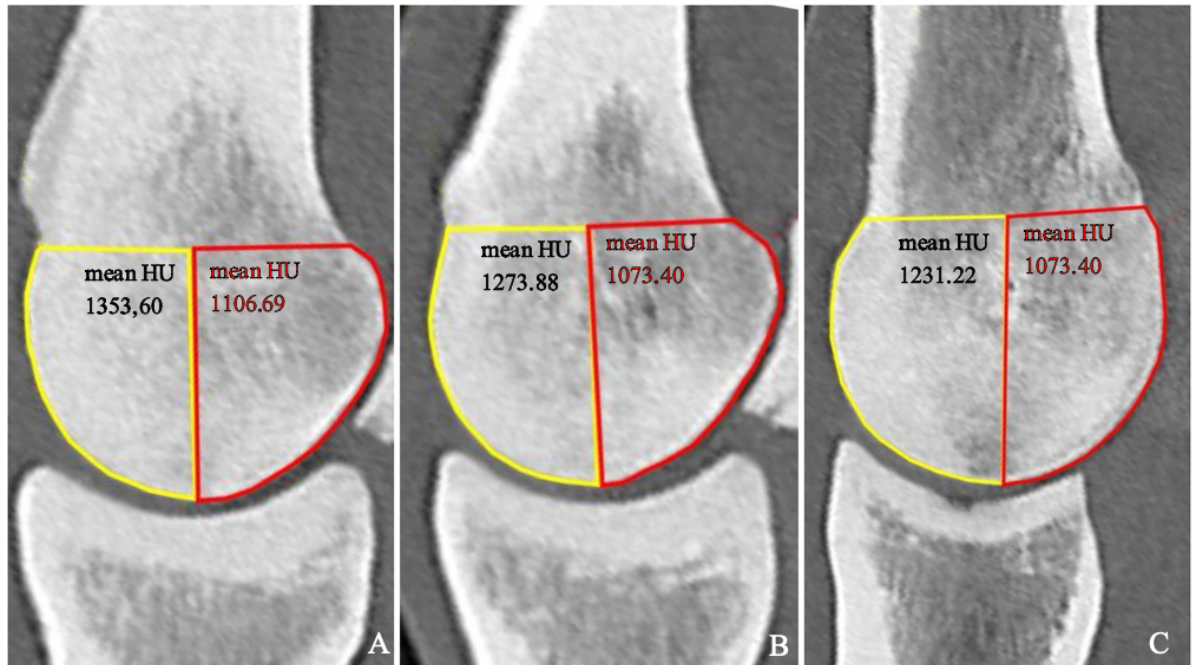


Figure 3. Representation of the mean Hounsfield Unit (HU) in the dorsal (yellow) and palmar (red) aspect of the A) medial condyle; B) lateral condyle and C) sagittal ridge

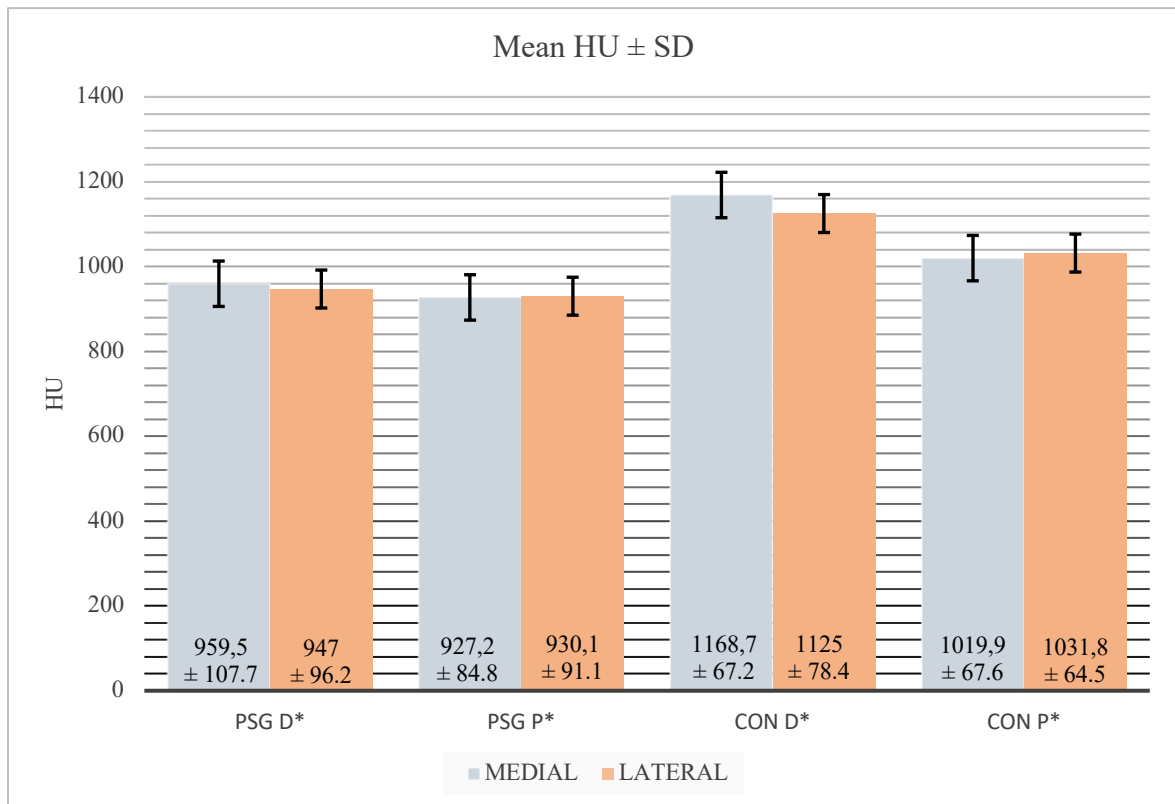


Figure 4. Results of the paired t-test comparing the mean Hounsfield Unit (HU) in the medial and lateral aspects. MED PSG – medial parasagittal groove; MED CON – medial condyle; LAT PSG – lateral parasagittal groove; LAT CON – lateral condyle *significance <0.001

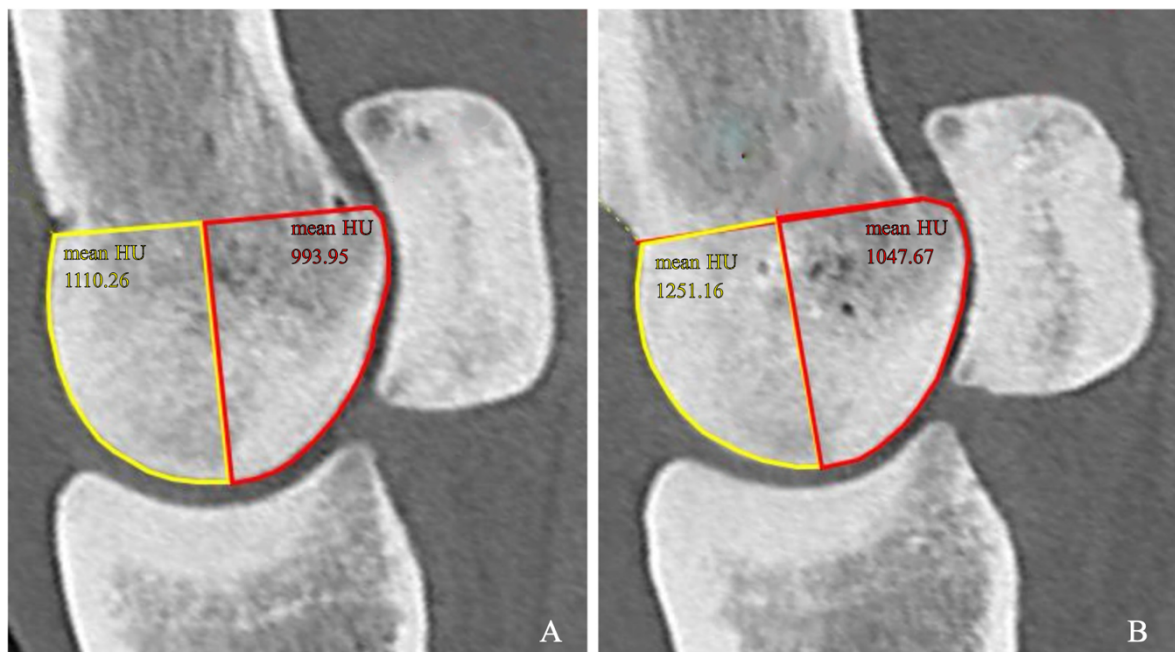


Figure 5. Representation of the mean Hounsfield Unit (HU) in the dorsal (yellow) and palmar (red) aspect of the A) lateral parasagittal groove; B) medial parasagittal groove.

There was a significant difference between the mean HU between the left and right forelimbs at all measurement sites ($p < 0.001$), except for the dorsal aspect of the medial parasagittal groove and the palmar aspect of the lateral parasagittal groove (Figure 6).

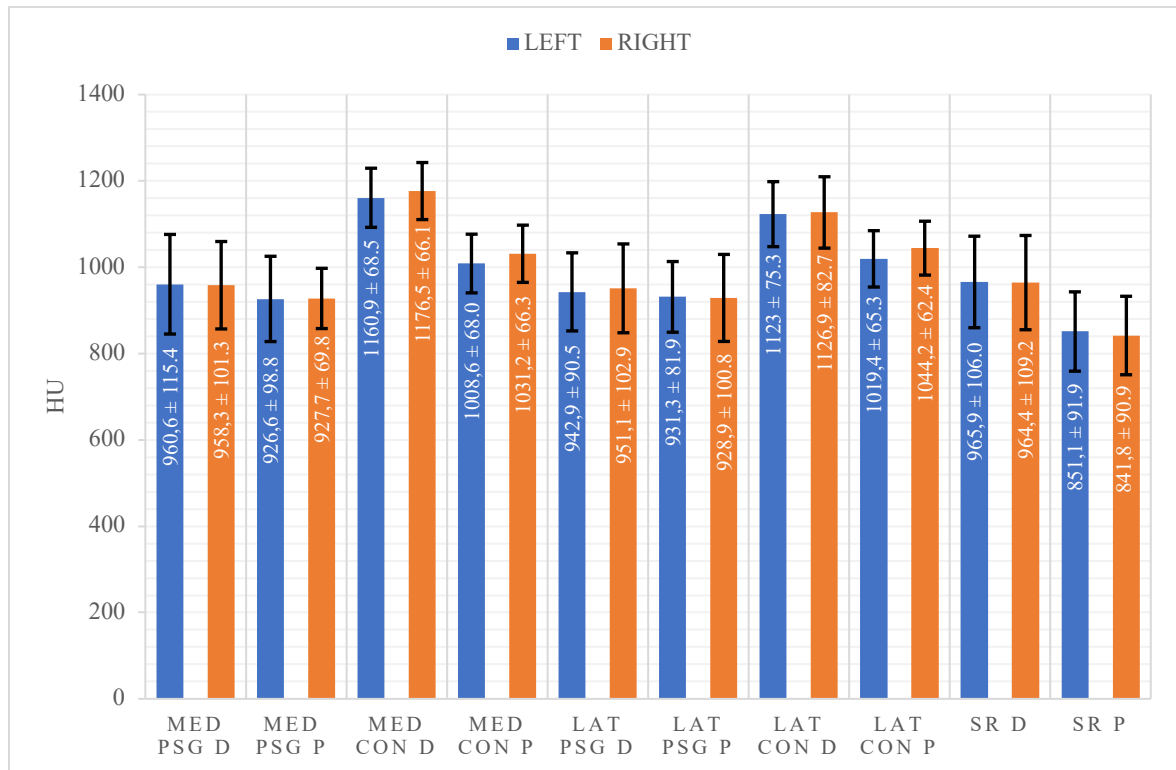


Figure 6. Results of the paired t-test comparing the mean HU of the right and left limb. MED PSG D – medial parasagittal groove dorsal aspect; MED PSG P – medial parasagittal groove palmar aspect; MED CON D – medial condyle dorsal aspect; MED CON P – medial condyle palmar aspect; LAT PSG P – lateral parasagittal groove palmar aspect; LAT CON D – lateral condyle dorsal aspect; LAT CON P – lateral condyle palmar aspect; SR D – sagittal ridge dorsal aspect; SR P – sagittal ridge palmar aspect

There was significant positive association between mean HU in the dorsal and palmar aspects of the medial condyle and age (dorsal: $p = 0.002$; palmar $p = 0.025$) and competition level (dorsal: $p < 0.001$; palmar: $p = 0.011$). In the lateral condyle, significant positive association with age ($p = 0.045$) and level ($p = 0.010$) was only seen in the dorsal aspect.

6. Discussion

This is the first study to objectively describe the densification pattern in the distal aspect of McIII in non-lame showjumpers in full work and competing regularly. Densification was measured by assessing the mean HU in ten regions of interest in all front limbs: the dorsal and palmar aspect of the lateral and medial condyle, the medial and lateral parasagittal grooves and the dorsal and palmar aspect of the sagittal ridge. This study is part of a longitudinal project; the population of horses is followed for two to three years, participating in re-examinations and diagnostic imaging eight months apart [5].

A previous study on the same study population as used in the current study, subjective MRI and CT image analysis revealed higher densification in the dorsal and palmar aspects of the medial condyle and in the palmar aspect of the lateral condyle in 80% of limbs [5], most likely an osseous adaption in response to exercise [6]. In agreement with our hypothesis and providing objective evidence to the previous subjective observations [5], we observed greater mean HU value in the dorsal and palmar aspect of the medial condyle and in the palmar aspect of the lateral condyle.

Our results of greater mean HU in the palmar aspects of the lateral condyles in comparison to palmar aspect of the medial condyle, is in agreement with the results of studies which investigated the presence of increased bone density of the distal McIII in response to cyclic loading in Thoroughbred racehorses. Results are consistent with repetitive shear forces exerted between the contact face of the proximal sesamoids bones and the palmar aspect of the condyles [32,39,46]. Riggs et al. found that in working Thoroughbred racehorses, the palmar aspect of the lateral condyle showed increased density compared to the palmar aspect of the medial condyle, which was not observed in horses there were not in work [32].

The increased HU values in the dorsal aspect of the medial condyle correspond with the area of peak strain during high-speed locomotion, and are consistent with the pattern of loading shifting from lateral to medial [19,24].

Age is also believed to influence the cortical bone's capacity to adapt to exercise. It is suggested that as horses age, their bones may become less responsive to the adaptive changes that typically result from mechanical loading [43]. We identified a positive association between the mean HU in both dorsal and palmar aspects of the medial condyle and age and competition level. In the lateral condyle, a positive significant association with age and level was only seen in the dorsal aspect. This is likely to be a cumulative response to exercise [46]; previous studies reported densification (sclerosis) with increasing training and career

progression [36]. Ground reaction forces acting on the forelimbs increase as the fence height increases [20], which can explain the significant positive association between mean HU in the dorsal and palmar aspect of the medial condyle and the dorsal aspect of the lateral condyle and competition level. Long term follow-up examinations, including a detailed work history are needed to highlight further correlations between density values of the distal McIII and the career progression of a showjumper. The impact of consistent jumping smaller jumps may be just as demanding and detrimental as fewer years spent jumping higher fences [22]. The jumping technique of a horse can affect load absorption on the forelimbs [20]. In the current study horses were not evaluated when jumping and objective assessment of such parameters in a repeatable way would be challenging.

A recent study documented longitudinal data on CT findings in the sagittal ridge of McIII in young Thoroughbred racehorses and showed that there was a significant increase in bone density of the sagittal ridge due to adaptive remodeling. A greater hyperattenuation was found in the dorsal than in the palmar aspect of the sagittal ridge [35]. This agrees with the results of this study, which also showed greater density in the dorsal aspect of the sagittal ridge of McIII. These similar findings are interesting in the light of the very different exercise flat racehorses and showjumpers are exposed to. Flatwork is an essential part of showjumpers' training and hyperextension of the fetlock is experienced to some degree in all equestrian disciplines [22].

In the current study, the mean HU value of the dorsal aspect of the distal McIII was significantly higher than the mean HU for the palmar aspect at all measurement sites. This might reflect the increased pressure exerted on the dorsal aspect of the fetlock during the landing phase of a jump, as the contact area between the McIII and proximal phalanx increases due to the applied vertical movement [19,22]. Different findings have been reported in a CT study on Thoroughbred racehorses, where density was lower in the dorsodistal aspect of the McIII than in the palmarodistal aspect [47]. Different biomechanical loading experienced by racehorses and showjumpers may explain the different results of these studies [22].

An earlier study found no significant topographical differences in the biochemical composition of the extracellular matrix of the articular cartilage between the lateral and medial condyle of the fetlock joint [18]. Biochemical components such as glycosaminoglycan (GAG), water and components of the collagen network were sampled to show the differences in cartilage composition in relation to different loading conditions [19]. Our study demonstrated a significant difference between the mean HU of the medial dorsal

and the lateral dorsal aspect. The medial dorsal aspect showed higher mean HU values in the condyle as well as in the parasagittal grooves. This is contrary to the results of the previous study which showed a significantly lower GAG content at the dorsal articular margin compared to central areas. A high GAG content is an indicator for loading, as it presented highest in constantly loaded areas of the joint [19]. The different results may be explained by different areas of investigation, as Brama et al. [19] focused on the cartilage surface of the fetlock and our study investigated density pattern of subchondral and trabecular bone in the fetlock joint. Furthermore, there is no information about the training or working history of this horse population, therefore results of the two studies should be compared with caution.

In our study, a significant difference between the left and right forelimbs was detected at all measurement sites. The palmar aspect of the condyles of the right front limb showed a significantly higher mean HU compared to the left forelimb. These results of the current study oppose the findings of a previous study, which used micro-CT to assess the microstructure of subchondral and trabecular bone of the palmarodistal aspect in the metacarpal condyles in Thoroughbred racehorses and revealed that bone tissue is denser, with thicker and more closely packed trabeculae in the condyles compared to the sagittal ridge and did not find any significant changes when comparing the both front limbs of their population of horses [47]. The laterality can be explained by a greater collective load absorption in the leading limb of a canter strike [15,24]. This is consistent with the results of the studies on the biochemical composition in articular cartilage, in which the right fetlock joint of 6 warmblood horses showed a higher GAG and water content, which is associated with higher load absorption [19]. Additionally, the cartilage on the right side was found to be stiffer than on the left side [19]. Motor laterality in the horse has been documented for several disciplines [19]. Motor laterality in a horse is a partly innate process. It progresses as horses mature and is partially shaped by the development of the brain, which can be affected by factors like training and stress [48]. Motor laterality in performance horses might influence their agility and speed during turns, which could be crucial for athletic success [49]. Racehorses for example, tend to be more successful in races with a right leading canter [48,49]. Although the direction of the racetrack might play a crucial role, it has been proposed that right lateralised horses should perform better on clockwise-courses than on anti-clockwise-courses and vice versa [49]. Showjumpers and dressage horses found to be more successful when preferring a left-lead, which increases loading the trailing right

forelimb and might explain the higher densification in the right forelimb at some measurement sites [50].

This study had some limitations. The main limitation is a relatively small sample population, from one geographical region. Furthermore, it cannot be ruled out that some horses had previous metacarpophalangeal joint disease that may have influenced our measurements. It was not possible to collect a detailed, cumulative work history.

Conclusions

In conclusion, there was greater degree of densification in the dorsal than the palmar aspect in all regions of distal third metacarpal bone in non-lame showjumpers, which reflects the loading pattern in this population of sports horses. These results should be considered when interpreting CT studies of the fetlock of lame showjumpers.

Further studies

I intend to perform the same measurements on the follow-up CT studies of the study population and will perform detailed analysis of the longitudinal data. Evaluation of potential changes in densification in the distal McIII with increasing age and cumulative exercise will further contribute to understanding of adaptive changes in showjumpers and to accurate interpretation of CT images of lame horses.

Abstract

Existing research focuses mainly on the description of magnetic resonance (MRI) and, more lately, computed tomographic (CT) findings in the fetlock joint of Thoroughbred racehorses. The importance of osseous lesions in the fetlocks of non-racing sports horses has been recognised, but there are limited publications on fan-beam CT findings in the fetlock of showjumpers and no objective CT findings have been reported.

The aim of the study was to describe the densification pattern in the distal aspect of the third metacarpal bone in non-lame showjumpers by assessing the mean Hounsfield Unit (HU) values.

Fan-beam CT images of both front fetlock regions of 31 non-lame showjumpers with no clinical signs or history of metacarpophalangeal joint disease were analysed. The mean HU values were obtained in ten regions of interest in the distal third metacarpal bone in all limbs: in the dorsal and palmar aspects of the medial and lateral condyles, of the medial and lateral parasagittal grooves and of the sagittal ridge. Descriptive data analyses were performed and paired t-tests were used to compare mean HU in different regions of interest. Linear logistic regression was performed to investigate associations between regions with the greatest densification and age and competition level.

The mean HU was greater in the dorsal aspect than the palmar aspect at all measurement sites ($p < 0.001$). A comparison between medial and lateral sides revealed that the mean HU was greater in the medial dorsal aspect, than in the lateral dorsal aspect ($p < 0.001$). In the palmar aspect of the condyles and parasagittal grooves, there was greater mean HU laterally than medially, while dorsally the mean HU was greater in the medial aspect ($p < 0.001$). There was a significant difference between the left and right forelimbs at all measurement sites; the greatest difference was seen in the palmar condyles (greater HU in the right than in the left forelimbs ($p < 0.001$)). There was significant positive association between mean HU in the dorsal and palmar aspects of the medial condyle and age (dorsal: $p = 0.002$; palmar $p = 0.025$) and competition level (dorsal: $p < 0.001$; palmar: $p = 0.011$). In the lateral condyle, significant positive association with age ($p = 0.045$) and level ($p = 0.010$) was only seen in the dorsal aspect.

The main limitation of this study is a relatively small sample population. Furthermore, it cannot be ruled out that some horses had previous metacarpophalangeal joint disease.

In conclusion, there was greater degree of densification in the dorsal than the palmar aspect in all regions of distal third metacarpal bone in non-lame showjumpers, which reflects the loading pattern in this population of sports horses.

Összefoglaló

Korábbi kutatások főként angol telivér versenylovak csüdájékának mágneses rezonancia (MRI) és újabban a komputertomográfiás (CT) vizsgálattal detektált elváltozásaira összpontosítanak. A csüdízület csontos elváltozásainak jelentőségét felismerték sportlovakban is, azonban korlátozott publikáció található fan-beam CT eredményekről díjugrató lovak csüdájékán, illetve nincs adat objektív CT vizsgálatról.

Tanulmányunk célja az volt, hogy leírja a hármás metacarpalis csont (McIII) distalis részén a csont denzitásának mértékét és eloszlását sántaságmentes díjugratásban versenyző lovakban, a Hounsfield egység (HU) átlagértékeinek vizsgálatával.

Harmincegy sántaságmentes ugróló (melyek kórelőzményében nem szerepelt elülső csüdízületi elváltozás) elülső csüdízületeiről készült fan-beam CT-felvételeit elemeztük. Az átlagos HU értékeket a McIII distalis részének tíz területén mértük: a medialis és lateralis condylus dorsalis és palmaris részein, a medialis és lateralis parasagittalis írkokban, valamint a sagittalis tarajon dorsalisán és palmarisan. Leíró statisztikai elemzéseket végeztünk, és páros t-tesztet alkalmaztunk a különböző területeken mért átlagos HU értékek összehasonlítására. Lineáris logisztikus regresszióval vizsgáltuk az egyes területeken mért legnagyobb denzitás és az életkor, illetve a versenyzési szint közötti esetleges összefüggéseket.

Az átlagos HU érték dorsalisán minden mérési ponton magasabb volt, mint a palmaris részeken ($p < 0,001$). A medialis és lateralis oldalak összehasonlításakor az átlagos HU érték nagyobb volt a medialis dorsalis részen, mint a lateralis dorsalis részen ($p < 0,001$). A condylusok és a parasagittalis írkok palmaris részén magasabb volt az átlagos HU érték a lateralis, mint a medialis oldalon, míg dorsalisán a medialis oldalon volt magasabb a HU érték ($p < 0,001$). Az átlagos HU érték minden mérési ponton szignifikánsan különbözött a bal és a jobb elülső végtag között ($p < 0,001$). Szignifikáns pozitív összefüggés volt a medialis condylus dorsalis és palmaris részén mért átlagos HU-értékek és az életkor (dorsalis: $p = 0,002$; palmaris: $p = 0,025$), valamint a versenyzési szint (dorsalis: $p < 0,001$; palmaris: $p = 0,011$) között. A lateralis condylusnak csak a dorsalis részén volt szignifikáns pozitív összefüggés az életkorral ($p = 0,045$) és a versenyzési szinttel ($p = 0,010$).

A tanulmány fő limitációja a viszonylag alacsony esetszám. Továbbá nem zárható ki, hogy egyes lovak korábban elülső csüdízületi kórképben szenvedtek.

Összefoglalva, dorsalisán nagyobb mértékű denzitást mértünk, mint palmarisan a McIII distalis epifiziének válemennyi régiójában sántaságmentes, díjugratásban versenyző

lovakban, ami tükrözi ezen sportlovak populációjában a McIII distalis részének terhelési eloszlását.

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Declarations

I hereby declare that this thesis is a presentation of my original research work and that no other sources were used other than what is cited. My specific task was to elaborate a methodology for standardised measurements of the distal third metacarpal bone by assessing the mean HU values. I performed all measurements. The work also involved statistical analysis of data and relating our results to existent literature and interpreting the findings.