In vitro biomechanical comparison of three parallel cortical screws versus three crossed cortical screws for arthrodesis of the equine proximal interphalangeal joint

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Abstract

The maintenance of rigid stability and compression of the pastern joint, similar to fracture repair, is required for successful pastern arthrodesis. Many techniques and variations on each technique have been studied biomechanically *in vitro* and confirm that some fixations provide more stability than others. In our study, the strength of a modified method of arthrodesis of the proximal interphalangeal joint using one axial and two abaxial screws was compared with a standard parallel arthrodesis technique by mechanically loading arthrodesis constructs on paired cadaveric limbs. These cadaveric limbs underwent mechanical destruction in a bend in a palmar (plantar)-to-dorsal direction. The assessment of the strength of arthrodesis constructs was based on the evaluation of the maximum loading force and the comparison of radiographs performed before and after loading. The measurements show that in 6 cases out of 7, the strength of the modified (crossed) arthrodesis method was higher compared to the parallel method.

Horse, pastern joint, arthrodesis, lag screw

The proximal interphalangeal (PIP) joint or pastern joint is classified as a diarthrodial, high load-low motion joint, which is formed from the distal aspect of the proximal phalanx (P1) and the proximal aspect of the middle phalanx (P2), which serves as a shock absorber for the distal part of the limb. Arthrodesis is a salvage procedure that is used for relief of pain associated with severe degenerative joint disease, stabilization of a limb after loss of supporting soft tissue structures, and/or treatment of complicated fractures involving a joint (Auer and Lischer 2019).

Conditions involving the PIP joint which necessitate arthrodesis are osteoarthritis, septic arthritis, comminuted fractures of the P1 or P2, luxation or subluxation of the PIP joint or osseous cyst like lesions. Because of the low motion and high load nature of this joint and the lack of interdigitation, attempts to manage the majority of common conditions of the PIP joint by methods other than arthrodesis usually fail to provide long-term success (Auer and Lischer 2019). Because the PIP joint is a low-motion joint, the goal of arthrodesis is to return the horse to athletic performance; however, the PIP joint must be ankylosed/arthrodesed in functional alignment to allow the metacarpophalangeal (MCP) joint and distal interphalangeal joint to compensate for the lost range of motion (Gudehus et al. 2011).

Till now, many techniques for arthrodesis of the proximal interphalangeal joint in horses have been described and compared, but only a few were performed on foals. One of the first and long-used techniques was arthrodesis using three trans articular 4.5 mm cortical screws placed in parallel (Steenhaut et al. 1985; Schneider et al. 1987) or in a converging direction (Zamos and Honnas 1993). In other cases, 3 transarticular 4.5 mm cortical screws in the crossed direction were used (Caron et al. 1990; Žert et al. 2013)

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and two 5.5 mm screws were drawn in the parallel direction (Watts et al. 2007). A study was also published in which two transarticular 4.5 mm cortical screws were placed in the transverse direction (Genetzky et al. 1981).

The arthrodesis method with parallel linear placement of the cortical screws in frontal plane provides minimal stability in the dorsal part of the PIP joint, which causes discomfort and considerable pain in patients due to excessive new bone formation and irritation of the extensor tendons or coffin joint (Auer and Lischer 2019). Stability has been increased in some cases by using 5.5 mm cortical screws instead of 4.5 mm cortical screws (MacLellan et al. 2001; Watt et al. 2001; Read et al. 2005). A previous publication showed sufficient results using a modified method of PIP joint arthrodesis (one crossed axial and two abaxial parallel screws) in two foals with severe osteochondrosis and insufficient development of joint structures (Žert et al. 2013).

The purpose of this *in vitro* study was to compare the strength of two surgical arthrodesis techniques. In the first case, there are three parallel 4.5 mm cortical screws. The modified method consists of one axial screw inserted from P2 to P1 and two abaxial screws placed in a parallel direction from P1 to P2. The first technique is currently preferred for PIP joint arthrodesis. We presumed that the modified method of arthrodesis would achieve higher strength using the same screws in terms of material, number and dimensions. The obtained results confirmed the increase in strength of the modified method in almost all tested samples.

Materials and Methods

Material collection

Nine pairs (n = 18) of normal cadaveric (sample) limbs (7 forelimb pairs, 2 hindlimb pairs), sectioned at the distal part of the metacarpus/metatarsus were collected from 7 foals of different ages (3 days to 8 weeks) euthanized for reasons unrelated to the PIP joint. The 9 pairs of limbs included 7 pairs of forelimbs and 2 pairs of hindlimbs, for a total of 18 surgical arthrodesis. After resection, the limbs were stored at −20 °C until the placement of the screws and subsequent assessment of the strength of the constructs. Limbs were left to thaw at room temperature for 24 h before instrumentation and testing. For comparison purposes, we assumed that there were no significant differences between the left and right limbs, so we proceeded randomly in selecting arthrodesis methods for each pair of limbs. The summary (Table 1) provides information on the number of samples, the horses' age, and the arthrodesis method used for a particular sampled limb.

Table 1. Basic information regarding the analysed limbs.

Sample number	Number of samples	Age when euthanized	Arthrodesis method
1	2 FL	6 weeks	RF (X), LF (III)
2	2 FL	8 weeks	RF (X), LF (III)
3	2 FL, 2 HL	3 days	RF, LH (X); LF, RH (III)
4	2 FL, 2 HL	4 weeks	LF, RH (X); RF, LH (III)
5	2 FL	1 week	RF (X), LF (III)
6	2 FL	2 weeks	RF (X), LF (III)
7	2 FL	2 weeks	RF (X), LF (III)

FL – Forelimb; HL - hind limb; RF - right front; LF - left front; RH - right hind; LH - left hind; X - modified (crossed) method; III - conventional (parallel) method

Positioning of screws

The samples were prepared for the placement of lag screws in the same way as in real procedures before the mechanical assessment of strength. The surgical field was prepared as standard. Standardized osteosynthetic instruments and materials were used in this study, namely a screwdriver shaft with a hexagonal screwdriver/quick coupling handle, universal drill guide 4.5/3.2; 3.2 mm quick coupling drills; 4.5 mm cortical self-tapping screws (DePuy Synthes, Johnson & Johnson, PA, USA). Three 4.5 mm cortical screws were applied to one limb of the pair in a parallel direction and to the contralateral limb in a modified (cross) direction. The young modulus for the 3 mm core diameter cortical screw is E = 210 GPA (grade point average) and section modulus 2.65 mm^3. Tapping did not need to be formed in the distal cortex due to the use of self-tapping cortical screws. The screw length was determined by measuring the hole depth with a depth gauge, so that after tightening the self-tapping cortical screw, its threaded part had to protrude 1–2 mm from the distal cortex to induce compression. The screws were manually tightened with a screwdriver to 2/3 of the possible/recommended torque. Prior to destruction, the position of the screws was documented radiologically (Plate I, Fig. 1).

Conventional (parallel) screw technique

Prior to insertion of cortical screws, three glide holes were formed from the distal articular surface of P1 in the disto-proximal direction using a 4.5 mm drill. The abaxial holes were guided in a divergent pattern. After repositioning the joint to a physiological position, guide holes in the short pastern bone were formed in the glide holes of the P1 through a drill guide using a 3.2 mm drill bit. It was not necessary to create threads due to the use of self-tapping cortical screws. The screw length was determined by measuring the hole depth with a depth gauge, and before instrumentation, cortical bone was not countersunk for the screw head (Plate II, Fig. 2). The screws were manually tightened with a screwdriver. Surgical sites were closed according to standard procedures.

Modified (cross) screw technique

In this technique, the axial screw was always positioned first in a lag fashion. The glide hole was formed in the dorsoproximal aspect of the P2 by a 4.5 mm drill through the proximal articular surface of the P2 at such an angle that the screw held firmly in the P2 and P1, to be applied in the distoproximal direction. The axial screw should pass through the joint near the junction of the dorsal ¼ and plantar/palmar ¾, thus ensuring the correct placement of the screw in P1, while minimizing damage to the coronary region and hoof wall. After creating this hole, glide holes were drilled to place two abaxial screws in parallel. The joint was repositioned to a physiological position, a drill guide was inserted into the glide hole in P2, and a guide hole was made in the distopalmar/plantar portion of P1 with a 3.2 mm drill bit. The axial screw was positioned and tightened to induce proper compression. Guide holes were drilled through the glide holes in P1 in the proximal direction into P2 with a 3.2 mm drill. The other two screws were placed abaxially, proximodistally, as in the previous method (Plate II, Fig. 2).

Biomechanical testing

The methodology for assessing the strength of arthrodesis constructs was based on the evaluation of the maximum loading force registered by the force sensor S9M (HBM, Darmstadt, Germany) and was also based on the comparison of radiographs realized not only at the end of the load, but also in the loading process. A special custom mounting frame (Plate II, Fig. 3, Plate III, Fig. 4) was designed for the experimental measurements, which made it possible to register the loading force during the whole process of testing the arthrodesis junction. After destruction, the samples with constructs were dissected to determine the extent of damage to the hard structures, and were finally macerated in sodium hydroxide solution for detailed evaluation.

The samples were placed in a bending with the palmar/plantar surface placed down and supported at two points (metacarpo/metatarsophalangeal joint and coronary border of the hoof) with plastic holders (Fig. 5b). The proximal portion of the samples was held in place by a dorsally disposed clamp (plastic) concavely shaped to encircle the medial and lateral portions of the fetlock and tightened with steel screws. The distance between these two points (A and B) was from 15 to 17 cm within the compared samples. Grooves in the mounting frame allowed flexibility as needed for differing limb sizes. To eliminate measurement errors, the samples were adjusted in the holders and the distances of the points were performed by one person. The constructs were loaded in a bending in a palmar (plantar)-to-dorsal direction (Fig. 5). Loading was applied at the site of the arthrodesis connection,

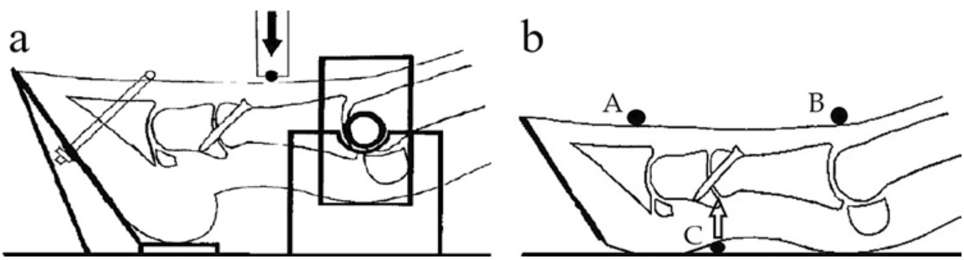

Fig. 5. Schematic comparison of the bending of the arthrodesis construct with the loading force: (a) arthrodesis construct tested in bending in a dorsal-to-palmar (plantar) direction published by Watt et al. 2001; (b) the samples were placed with the palmar/plantar surface down and supported at two points (A and B). Point A represents the level of the coronary border of the hoof and point B the level of the fetlock joint. Loading of the constructs in a bending at the site of the arthrodesis connection, directly into the pastern joint space (C) in a palmar (plantar)-to-dorsal direction.

directly into the pastern joint space in a palmar (plantar)-to-dorsal direction with a plastic profile. Constructs were loaded to failure with a displacement rate (vertical displacement) of 15 mm/min (the first two constructs 12 mm/min). The loading force during destruction was registered by an S9M tension load cell and continuously registered by the Quantum X MX840 (HBM) measuring amplifiers. The resulting values were processed with Catman Easy software.

Results

Cortical self-tapping screws were applied in samples (18) in the desired direction with slight deviations and adequate length to induce PIP joint arthrodesis, but in sample no. 7, a guide hole for an axial cross screw in P1 was drilled close to the distopalmar border of P1, which caused insufficient holding of the screw in the bone. During the biomechanical loading, no disturbance of the skin integrity by the plastic holder was observed on the palmar surface of the cadaveric limbs. The vertical displacement rate was 12 mm/min for samples no. 1 and 2, 15 mm/min for samples no. 3, 4, 5, 6 and 7. In two of the seven cases (samples no. 2 and 3), radiographic imaging was performed during biomechanical loading. In none of the cases were the screws damaged; only pulling out from bone, which was confirmed by dissection and radiographs of the samples after destruction (Plate I, Fig. 1). The proximal growth plate of P2 was broken in most cases in the lateromedial direction. The process of the loading force was recorded by Catman Easy software and shown in graphs (Plate III, Fig. 6). The values of the maximum load of the arthrodesis constructs of the samples are shown in Table 2. Comparing the maximum values of the loading force for both methods of arthrodesis of the PIP joint, we can state that in sample no. 1 the modified arthrodesis method reached a maximum value of 780 Newton (N), whereas the parallel method 680 N. After left forelimb loading (parallel method), a rupture was registered at the site of the arthrodesis junction at 1 min, which represented a sudden drop in the curve characterized by the release of the construct. In the case of right forelimb (cross method), this phenomenon was not observed, but at some point (1 min) the force sensor registered a slight decrease, which was interpreted as a connection failure. It means that the difference in the maximum values was not so significant, but the modified method withstood about 100 N more load at the same acting force. The maximum load values for the following samples are given in the Table 2.

Table 2. Values of maximum load of arthrodesis constructs of cadaveric limbs.

	Maximum load of the arthrodesis constructs (N)			
	LF	RF	LH	RH
Sample 1	680 (III)	780 (X)		
Sample 2	400 (III)	1140 (X)		
Sample 3	270 (III)	320 (X)	340 (III)	360 (X)
Sample 4	580 (III)	1000 (X)	660 (III)	1220 (X)
Sample 5	460 (III)	860 (X)		
Sample 6	370 (III)	500 (X)		
Sample 7	570 (III)	340 (X)		

N - Newton; LF - left front; RF - right front; LH - left hind; RH - right hind; X - modified (crossed) method; III - conventional (parallel) method

We conclude that the arthrodesis connection with the parallel direction of the screws withstood a higher load (almost two times) compared to the modified (cross) direction. This difference is explained by the incorrect placement of the axial screw in P1 (cross method) and thus by the insufficient connection of the adjacent bones.

Experimental measurements show that in six of the seven samples (no.1, 2, 3, 4, 5 and 6), the strength of the cross method was greater compared to the conventional method. A significant difference in maximum bending and strength was noted in samples no. 2, 4, and 5 (Fig. 6), where the crossed method of arthrodesis withstood a two to three times greater load under the same bending. In case of sample no. 7, values were recorded, indicating greater strength of the conventional method, difference was about 270 N which was largely due to incorrect drilling of the axial screw hole, the stability of which in the bone was minimal.

Discussion

Factors that may limit the success of PIP joint arthrodesis include the ability to maintain cortical screws in very young, insufficiently ossified bones (P1 and P2) and the presence of growth plate cartilage. In order to keep the cortical screws in the bone, it is necessary to minimize or even completely omit the countersinking of the hole in the dorsal cortical bone for the screw head; manual tapping and tightening of the screws is recommended (Watts et al. 2007). The methodology in the experimental part differed from the published studies in several ways. Watt et al. (2001) describe in their study that palmar/plantar structures such as the interosseous muscle and the accessory ligament of the deep digital flexor tendon can partially affect the strength and/or maximum bending moment of the arthrodesis construct by creating the so-called spring effect. The purpose of keeping palmar/plantar structures was to remain close to the conditions under clinical loading of the limbs. The cadaveric limbs (thoracic and pelvic) were resected at the level of the distal metacarpus/metatarsus, thus the function of the structures was mechanically impaired. In our study, no difference in strength was observed between the arthrodesis constructs of the thoracic and pelvic limbs. It should be noted that only in two cases (samples 3 and 4) were the thoracic and pelvic limbs evaluated, with age differences (3 days and 4 weeks). Our results are consistent with biomechanical evaluations (Watt et al. 2002; Read et al. 2005), in which no significant differences in strength and maximum bending moment were reported between the thoracic and pelvic limb constructs.

In our study, we removed the articular cartilage on the distal articular surface of P1 and the proximal articular surface of P2 in comparison with published studies. The authors of these studies argue about the possible influence of assessment and evaluation of individual arthrodesis constructs in incomplete cartilage debridement, which would cause uneven friction between constructs (Watt et al. 2001). The collected cadaveric limbs were subjected to PIP joint arthrodesis using osteosynthetic materials (cortical self-tapping 4.5 mm screws) in such a way that within a pair of limbs, screws were placed in one limb in a parallel direction and in a contralateral limb in a modified (cross) direction. In published experimental studies, the screws were placed only after the glide holes were formed by a combined aiming device (Synthes, Wayne, PA, USA) to guide the most accurate direction (Watt et al. 2001; Read et al. 2005; Carmalt et al. 2010; Sod et al. 2010; Wolker et al. 2011).

No aiming device was used in the creation of the glide holes in our study, so it cannot be excluded that the differences in the achieved results were also influenced by the quality of the implementation of the arthrodesis connection. A certain asymmetry of the placed screws in both the parallel and the modified method of arthrodesis of the PIP joint was confirmed by performing radiographs before testing (destruction). Most published biomechanical studies examining PIP joint arthrodesis focus on single loading of constructs to failure (Easter and Watkins 1998; Watt et al. 2001; Watt et al. 2002; Read et al. 2005). In these studies, constructs were tested only in modified dorsopalmar/plantar three-point bending (Watt et al. 2001; Watt et al. 2002; Read et al. 2005). Although these data are important, they cannot be transferred to clinical situations, as cyclic loading plays a greater role in arthrodesis construct failure than a single loading (Watt et al. 2001). Arguments in support of the axial compression model are that it more accurately mimics the *in vivo* situation; however, proponents of the three-point bending model suggest that this technique only tests the arthrodesis construct and thus represents a more thorough evaluation of the surgical procedure (Carmalt et al. 2010). Clinically, the PIP joint is loaded in a combination of bending, axial compression, and torsion (Watt et al. 2001). Testing of arthrodesis constructs in torsion, compression or axial loading is a relatively technically demanding process (Easter and Watkins 1998; Galuppo et al. 2000; Sod et al. 2010; Sod et al. 2011; Zoppa et al. 2011; Vidović et al. 2020). The hypothesis of the *in vitro* study was that arthrodesis constructs are the weakest in bending, and we wanted to test these constructs under the most severe loading conditions. In retrospective studies, constructs were destroyed in the dorsopalmar/plantar direction, with a loading force positioned 1.5 cm proximal to the screw heads (Watt et al. 2001; Read et al. 2005; Carmalt et al. 2010; Wolker et al. 2011). Our destruction process was characterized by palmar/plantar-dorsal destruction of the constructs in order to minimize the effect of palmar/plantar structures on the strength and stability of the constructs.

The constructs in our study were loaded at a speed of 15 mm/min, but in two cases (samples no. 1 and 2) a speed of 12 mm/min was chosen due to the realization of radiographs. For the experimental measurement, a loading device was designed which made it possible to register the loading force during the whole process of loading the arthrodesis construct. A necessary condition for such comparative measurements is the ability to perform the experiment under the same conditions. In order to meet this condition, it was necessary to design a special device for holding the cadaveric limbs. The fixation of the cadaveric limbs in our case was identical to the studies (Watt et al. 2001; Read et al. 2005; Carmalt et al. 2010), but with the difference that the hoof of the limb was not fixed with a screw but was in the dorsal part fixed with a plastic clamp copying the surface of the hoof wall. To eliminate measurement errors, one person performed the adjustment of the position of the loading device (plastic holder) and the fastening of the limbs. Prior to loading, this plastic holder with a milled 3 mm profile was precisely positioned in the PIP joint space for direct loading of the arthrodesis constructs. It should be noted that experimental measurements were performed on the cadaveric limbs of foals of different ages, different ossifications of bone structures and with an open proximal growth plate of P2, which could also cause deviations in the results obtained.

Our results support the hypothesis that the modified arthrodesis method will provide significantly better stability and strength even in a single failure test in the palmar/plantar to dorsal direction compared to the standard parallel method. The results of this study supported the main hypotheses and demonstrated the clinical significance of modified proximal interphalangeal arthrodesis in a relatively small but representative samples. The initial study compares the standard arthrodesis technique in foals and young horses and the modified bending technique with the palmar/plantar to dorsal loading of the constructs. The limiting factors of the *in vitro* study comparing the two methods of arthrodesis were a wide age range of cadaveric limbs of foals and different degrees of ossification, biomechanical loading and the related process of dehydration and decomposition of the limbs. From the point of view of the surgical procedure, a special combined aiming device for the symmetrical and precise creation of holes for cortical screws was absent. The issue of the use of self-tapping cortical screws has been widely discussed, as their design and shape properties need to be respected. The variability in the resulting values was also influenced by the method and direction of loading constructs.

Our clinical studies confirm the possibility of using a modified method of arthrodesis of the proximal interphalangeal joint in clinical cases of joint involvement with developmental disorders (osteochondrosis, subchondral bone cyst) or traumatic conditions at a very early age. For elderly patients with joint instability, the tested construct is not rigid, and there is a risk of failure under load. The age restriction on the use of this method will be the subject of further study. Recently, a clinical study was published on the successful arthrodesis of the pastern joint by a modified method in combination with the filling of the subchondral bone cyst in the distal part of P1 with calcium hydrogen phosphate (Kolʼvek et al. 2021).

The experimental study demonstrated technical feasibility and applicability of the modified method of proximal interphalangeal joint arthrodesis with crossed screw placement in the treatment of joint injuries in young horses. In comparison with the parallel placement of the screws on cadaveric limbs, the modified construct was shown to have higher flexural stiffness in the in the palmar(plantar)-to-dorsal direction in six out of seven samples. The failure of the modified construct in one sample was due to incorrect axial screw placement in the proximodorsal aspect of P2 and reduced skeletal mineralization of this sample. To indicate the use of the modified method in practice, it is important to take into account the degree of maturity and ossification of the patient's skeleton.

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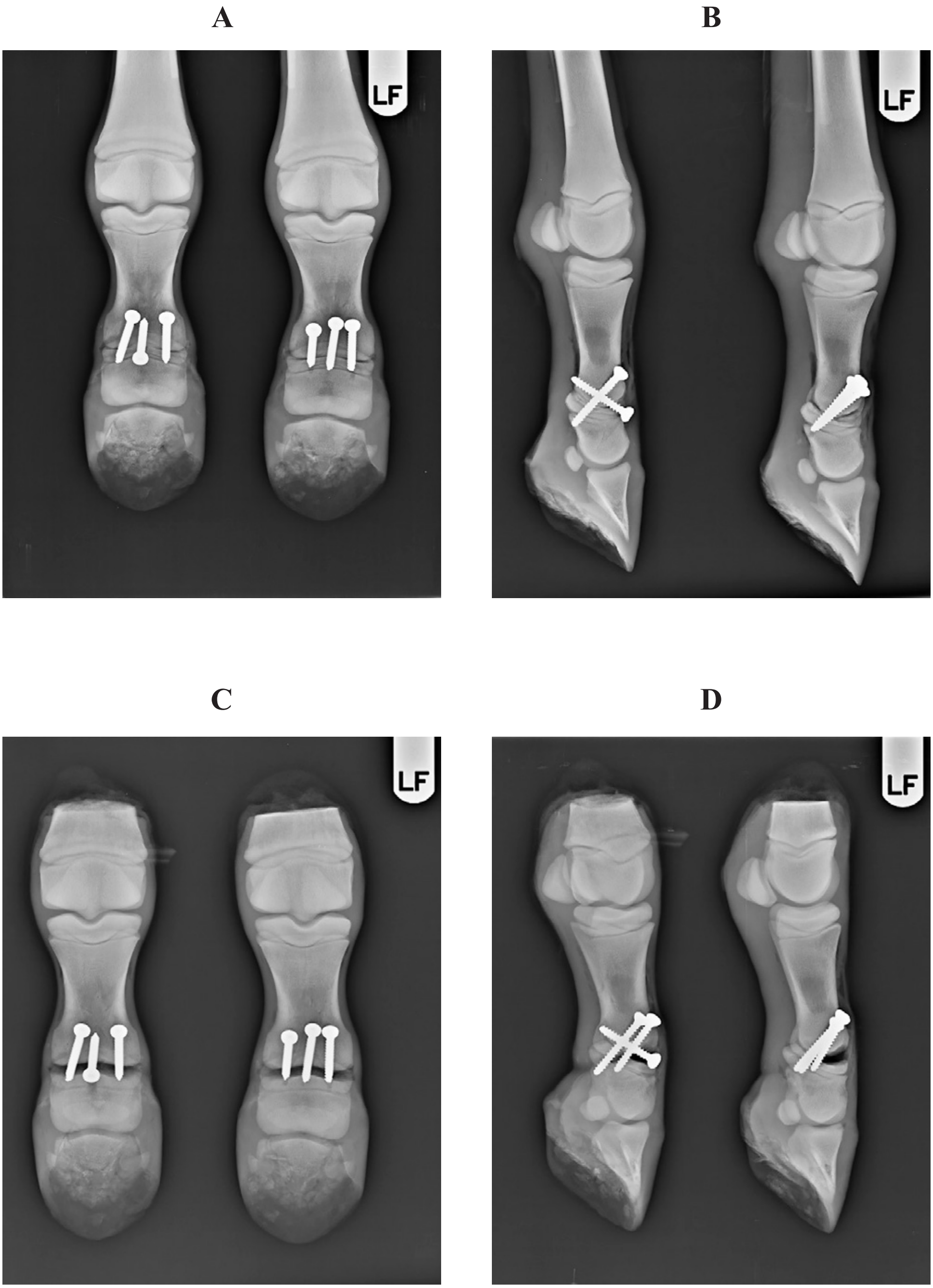

Fig. 1. Radiographs of the distal part of the limbs in sample no. 5. Dorsopalmar view of the thoracic limbs (a, c) and lateromedial view of the thoracic limbs (b, d). Radiographs before destruction (a, b) showed the relative good alignment of the screws and after destruction (c, d) enlargement of the pastern joint space without breakage of screws.

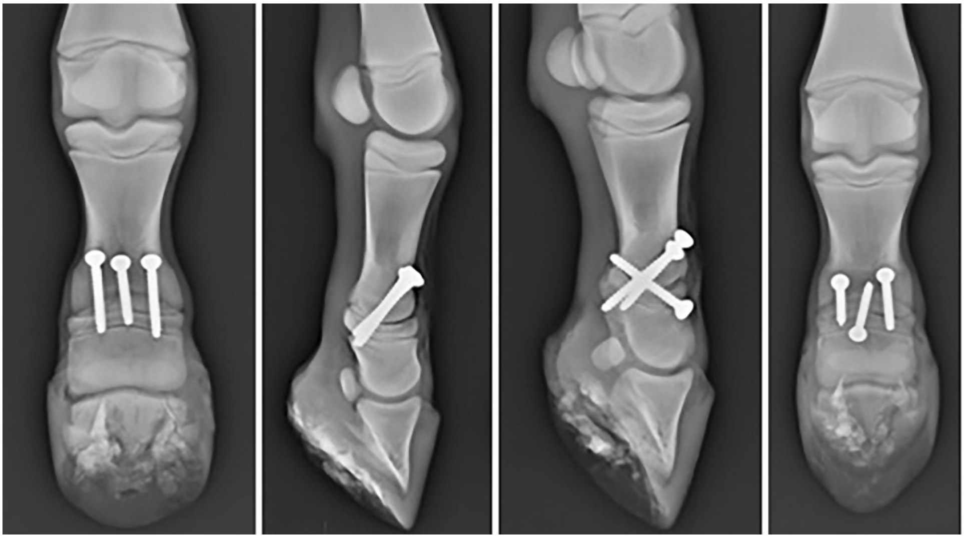

Fig. 2. Postoperative radiographs of the parallel (a, b) and modified (c, d) method of the proximal interphalangeal (PIP) joint arthrodesis

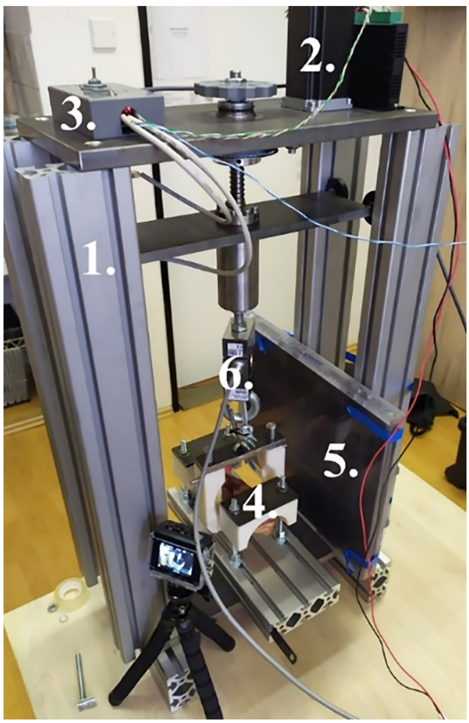

Fig. 3. Loading, measuring and evaluation equipment. Camera recording during the destruction and also radiographic examination during the destruction.
1 - Load frame, 2 - motor with drive shaft, 3 - control button, 4 - plastic holder, 5 - flat panel detector, 6 - force sensor

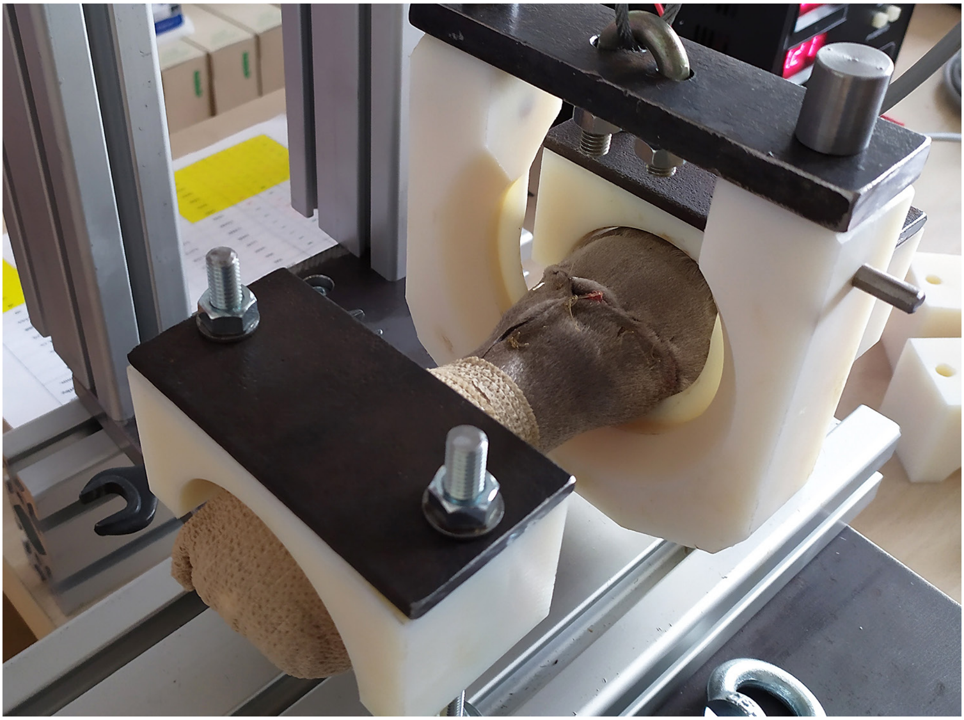

Fig. 4. Detailed view of a limb placed in a silon holder device with two mounting clamps

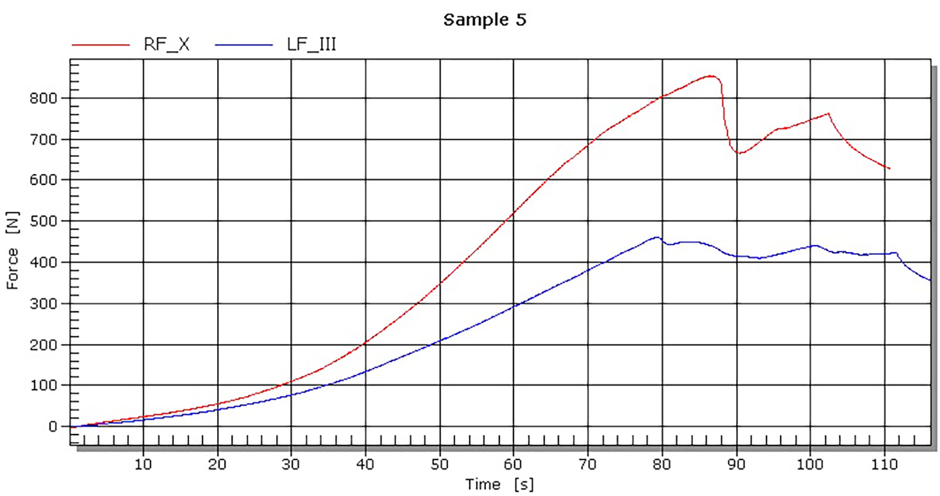

Fig. 6. Time record of the loading force of sample no. 5. The maximum values of the loading force for both methods of arthrodesis of the proximal interphalangeal (PIP) joint, modified arthrodesis method reached a maximum value of 860 N and the parallel method 460 N. From measured values it is clear that the difference was relatively significant, about 400 N, which represents two times the strength of the arthrodesis connection using the modified method.

N - Newton, RF- right front limb, LF - left front limb. “X” – modified (cross) method and “III” conventional (parallel) method.