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Original article

Biomechanical study in vitro on the use of self-designed external fixator in diaphyseal III metacarpal fractures in horses

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Abstract

Diaphyseal fractures of the III metacarpal bone represent 22% of all fractures of the long bones in horses. Treatment of such cases is difficult. The most popular solution used in these types of fractures is two plates applied directly to the bone surface, but they are not applicable on contaminated and infected fractures.

External fixators are quite commonly used in human medicine, although in veterinary practice there is no typical stabilizer designed for the treatment of diaphyseal fractures of the III metacarpal bone so far. In this study, an external semicircular fixator of our own design was used and in vitro strength tests were conducted to determine the maximum force which would lead to the destruction of non-fractured bone and fractured bone treated with the stabilizer.

On the basis of the strength tests, we can conclude that the stabilizer can be strong enough to allow the horse to stand up after surgery. It also has many favorable features which make it easy to assemble and to take care of a wound, while being safe enough for the animal at the same time.

Key words: external stabilizer, diaphyseal fractures, III metacarpal bones, bone fractures, equine surgery

Introduction

Diaphyseal fractures of the III metacarpal bone represent 22% of all fractures of the long bones (McClure et al. 1988). If all fractures of the III meta-

tarsal bone are taken into consideration, the number will reach 33% (McClure et al. 1988). Treatment of diaphyseal fractures of the III metacarpal bone in horses is difficult (Auer 2006, Bischofberger et al. 2009, McClure et al. 1988). The main problem is the

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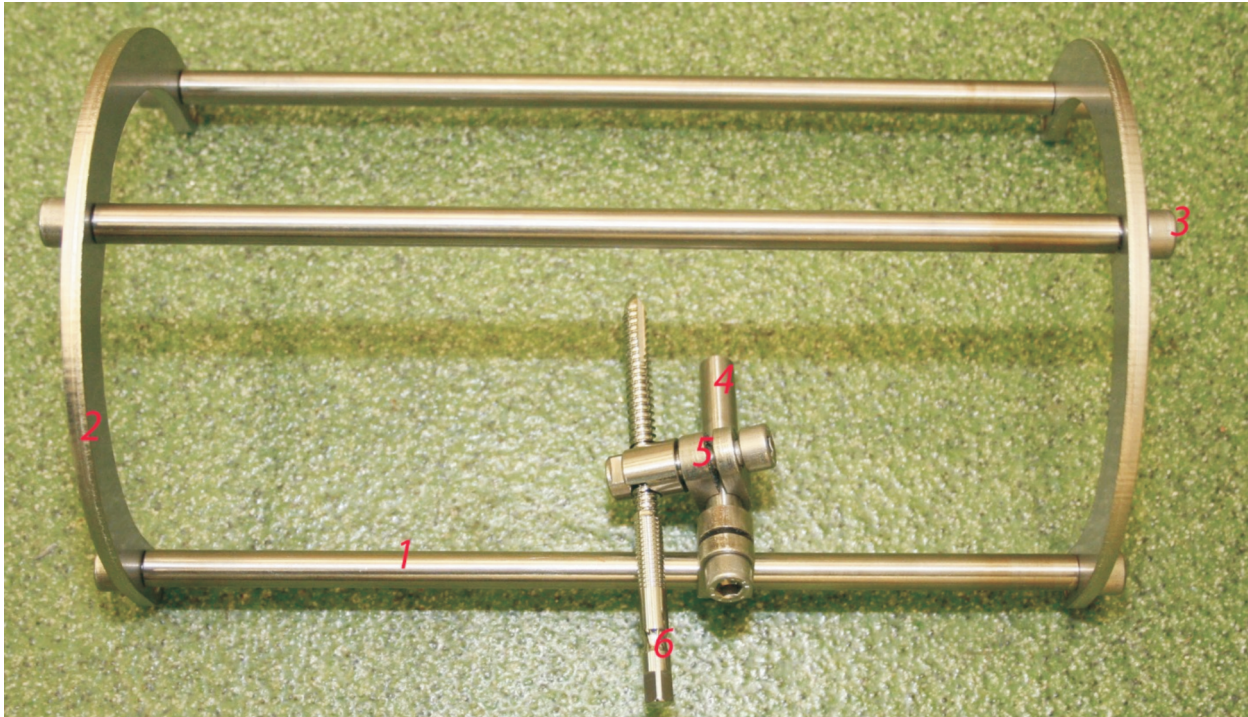


Fig. 1. Stabilizer with arm, connector and screw. 1- 8mm metal rod; 2 – horseshoe; 3 – mounting screw; 4 – arm to attach the screw connectors; 5 – screw connector; 6 – 6mm Apex-type self-tapping screw.

small thickness of soft tissues surrounding the bone. The most popular solution used in these types of fractures is two plates applied directly to the bone surface (Auer 2006, Richardson 2006). Treatment also includes the use of various plate modifications – from DCP (dynamic compression plate), LC-DCP (low contact dynamic compression plate), LCP (locking compression plate) and the prototype EM-DCP (equine metacarpal dynamic compression plate) (Sod et al. 2005a,b, Auer 2006, Richardson 2006, Sod et al. 2008). However, tissue suturing may be difficult or impossible. Moreover, in open fracture cases, contamination and infection occurs and using plates is impossible. Regarding the use of intramedullary implants, there were attempts at the use of interlocking nail, but this solution did not become everyday practice (McDuffee et al. 1994, Hertel 1996, Fitch et al. 2001, Galuppo et al. 2002). The most significant problem was the low strength of the structure. Furthermore, in the case of open fractures, the same limitations as in the case of plate use occur. One possibility seems to be the use of bone-attached implants covered with polymer dressing – cast transfixation (McClure et al. 1996, Scott et al. 2000). However, stabilization of fragments as obtained by this method of treatment is insufficient and, despite this, loosening

of the implant connection with a dressing will occur (McClure et al. 1994a,b, McClure et al. 1996, Sullins and McIlwraith 1987, Joyce et al. 2006, Lescun et al. 2007). Application of a dressing comprising a larger portion of the limb limits mobility in the joints, which is not desirable.

External fixators in the treatment of long bone fractures in horses are rarely used (Sullins and McIlwraith 1987, Nemeth and Back 1991, Cervantez et al. 1996, Leskun et al. 2007, Nash and Nunamaker 2008, De Godoy et al. 2009). Attempts to use an Ilizarov fixator in horses showed that the strength in this treatment is not sufficient (Cervantez et al. 1996). However, this method is applicable to the treatment of selected fractures of long bones in ruminants (Cervantes et al. 1996, Aithal et al. 2004, Bilgili et al. 2008, Aithal et al. 2010). Also, external fixators are quite commonly used in the treatment of selected fractures in humans (Ramotowski et al. 1998), although in veterinary practice there is so far no typical stabilizer designed for the treatment of diaphyseal fractures of the III metacarpal bone.

The purpose of the in vitro strength tests was to determine the maximum force which would lead to the destruction of non-fractured bone and fractured bone treated with the stabilizer.

Materials and Methods

In this study, an external semicircular fixator of our own design was used, shown in Figure 1, and the third metacarpal bones derived from 56 healthy horses slaughtered in a slaughterhouse between 2-7 years of age with an average body weight of 500-550 kg. After cutting the legs at the level of the carpal joints, III and metacarpal bones with splint bones together were collected by removing all the soft tissue with a knife. In the next step the bones were placed in the freezer.

Strength tests: compression and three-point bending tests were performed using a Tira Test 2300 machine. In both tests the loading speed was the same – 2 mm/min. In the three-point bending test the distance between supports was 150 mm and the bone's palmar surface was leaned on the support, while the pressure was exerted on the dorsal side. During the tests the maximum force value was recorded, which is the highest recorded value of the force. Strength tests were carried out on completely defrosted bones. In order to achieve this, the bones were removed from the freezer for 24 hours before the planned tests and stored at room temperature.

Strength tests were carried out in two stages:

Step 1 – to determine the value of maximum force for non-fractured bones

The aim was to determine the value of a force leading to a fracture of non-fractured bone. For this stage, 14 pairs of bones were used. The test was terminated at the time the bone fractured.

a) three-point bending test – 14 bones from the left leg

b) compression test along the long axis of the bone – 14 bones from the right leg.

Step 2 – to determine the value of maximum force for fractured bones fixed with stabilizer.

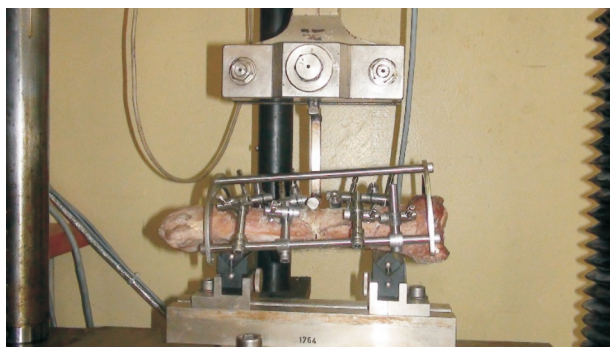


Fig. 2. Broken bone with stabilizer installed on the study table: Three-point bending test.

In this stage 84 bones were used from 42 horses. An external fixator was used to stabilize the bone fragments together (Fig. 1) as well as self-tapping

screws with a diameter of 6 mm and a length of 95 and 100 mm, which were combined with the structure of the stabilizer by clamps. For maximum strength of the structure, the clamps were placed as close to the bone as possible. After setting up the stabilizer, the bones were cut with oscillating saw, in the middle of the diaphysis to simulate the transverse fracture of it.

a) three-point bending test (Fig. 2).

At this stage 78 bones were used (36 pairs and 6 left bones). Self-tapping screws were placed in the bone in three variants: the first – four screws in each bone fragment (2,2-2,2), the second – 5 screws in each fragment (2,2,1-1,2,2), the third – 5 screws in each of the bone fragments (1,2,2-2,2,1). The difference between option 2 and 3 lies in the fact that 1 screw was placed on the central rod, closer to the fracture line in each bone fragment (second variant) or 2 screws were placed on external bars. In variants 2 and 3, 26 bones were used (13 pairs), while in the first variant 26 bones were also used, but from 16 horses (10 pairs and 6 left bones). The configuration of the screw position in each of the variants was the same. In order to obtain the maximum strength of fixation, they were placed in a tent style. The study was terminated at the point of no force increase and continuing increase in deformation.

b) compression test (Fig. 3)

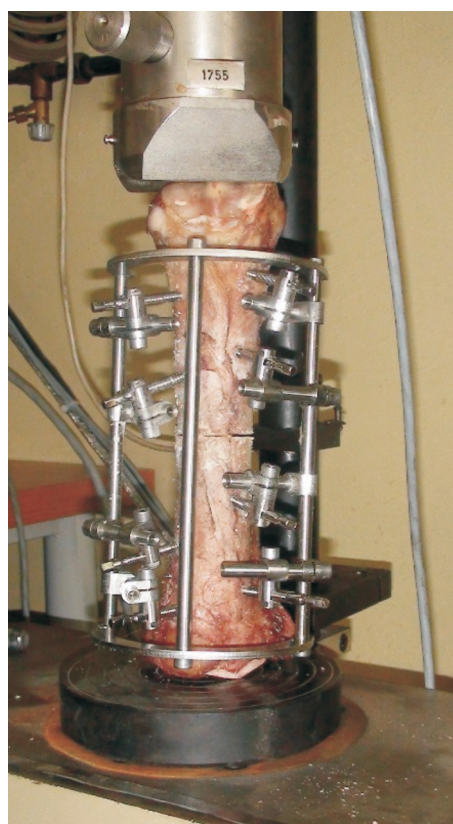


Fig. 3. Fractured bone with installed stabilizer on the study table. Compression test along the long axis of the bone

Table 1. Values of maximal force (Fmax.) expressed in kN obtained for non-broken bones.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	mean	SD
horse	1	2	3	4	5	6	7	8	9	10	14	16	26	56		
Fmax. [kN] L bending	22.43	17.23	16.23	19.10	20.73	20.09	20.09	18.69	13.31	20.03	19.56	13.49	14.60	23.24	18.49	3.11
Fmax. [kN] P compression	100	40.88	88.9	62.96	78.44	59.81	53.38	52.16	64.37	98.24	65.18	31.77	64.60	85.36	67.58	20.42

Table 2. Values of maximal force (Fmax.) expressed in kN obtained in three-point bending test for bone fixed in Variant 1.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	mean	SD	
horse	20L	22L	28L	15L	18L	25L	54L	54P	46L	46P	48L	48P	52L	52P	17L	17P	24L	24P	44L	44P	31L	31P	32L	32P	35L	35P			
Fmax	3.15	1.57	2.33	3.02	2.84	2.96	2.68	2.89	3.02	2.88	2.98	2.84	3.08	3.02	1.81	2.86	2.68	3.03	2.27	3.44	2.96	3.12	2.89	2.73	3.12	2.94	2.78	0.41	0.41

Table 3. Values of maximal force (Fmax.) expressed in kN obtained in three-point bending test for bone fixed in Variant 2.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	mean	SD	
horse	53L	53P	42L	42P	41L	41P	39L	39P	38L	38P	37L	37P	36L	36P	12L	12P	13L	13P	21L	21P	19L	19P	23L	23P	30L	30P			
Fmax	3.42	3.36	3.16	3.28	3.42	3.29	2.98	3.12	3.56	3.62	3.34	3.12	3.14	3.08	3.27	2.92	3.27	3.32	2.62	2.68	3.56	3.44	3.38	3.38	2.62	3.38	3.22	0.27	0.27

Table 4. Values of maximal force (Fmax.) expressed in kN obtained in three-point bending test for bone fixed in Variant 3.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	mean	SD	
horse	57L	57P	43L	43P	45L	45P	47L	47P	49L	49P	51L	51P	55L	55P	33L	33P	34L	34P	40L	40P	11L	11P	27L	27P	29L	29P			
Fmax	3.08	2.86	2.86	2.42	2.96	3.16	2.68	2.45	2.89	3.08	2.36	2.67	2.18	2.48	3.91	2.21	4.03	1.69	2.92	3.09	2.45	2.97	1.92	2.68	1.81	2.45	2.70	0.55	0.55

Table 5. Values of maximal force (Fmax.) expressed in kN obtained in compression test for fixed bones.

n	1	2	3	4	5	6
horse	20P	22P	28P	15P	18P	25P
Fmax [kN]	24.94	26.46	26.05	26.95	25.04	26.32

The test was conducted on 6 right bones. The left bones were used in the three-point bending test in the first variant. The study was terminated after exceeding the value of 25 kN.

Statistical methods

All calculations and graphs were performed using Statistica 10 (StatSoft Inc.).

Apart from counting the average value and standard deviation, other features were determined as follows:

- a) comparison of the maximum force obtained in the three-point bending bone tests, which were fixed up with the use of an external fixator in 3 variants
- b) determining the relationship of the maximum force of bone fixation in three variants depending on the cross-sectional diaphyseal field in one 1/2 length of a bone

The arithmetic mean was obtained from the values of the maximum force in groups 2 and 3. In the first group, 6 left legs from 6 horses were additionally tested. At the end, 16 measurements were obtained in group 1 and 13 in groups 2 and 3 respectively.

The resultant maximum forces in three different variants were compared using a one-factor one-variable analysis of variance (one-way ANOVA). The homogeneity of variance between groups was checked using the Brown-Forsyth test. Post-hoc analysis was performed with a reasonable significant difference Tukey test for unequal sample probes. In all tests, the significance level adopted (α) was equal to 0.05.

Results

1. Determination of maximum force for non-fractured bones

a. the average value of maximum strength for bones subjected to three-point bending was 18.49 kN with a standard deviation of 3.11 kN. The results for all bones are shown in Table 1.

b. the average maximum force for the compression test was 67.58 kN, with a 20.42 kN standard deviation. The results for each bone are shown in Table 1.

2. Determination of maximum force for fractured bones fixed using a stabilizer.

a) three-point bending test

First variant – the average value of maximum force was 2.78 kN. The results for all fixations are shown in Table 2.

Second variant – the average value of maximum force was 3.22 kN. Values for all fixations are shown in Table 3.

Third variant – the average value of maximum force was 2.70 kN. The results for each fixation are shown in Table 4.

b) compression test along the long axis of the bone. The results are shown in Table 5.

Assessment of damage after strength tests

1. Fixed bones

a) compression test – no defects were observed either within the bone or the stabilizers. The test was stopped after approaching the value of 25kN in order to avoid damage to the components of the stabilizer.

b) three-point bending test

There were no failures within the bone in any case, although damage to the components of the stabilizer and screws occurred. In the first and second variant, bending (plastic deformation) of screws placed near the fracture line was noted. In the third variant the most commonly bent screw was the one mounted on the central rod but placed in the fragments further away from the fracture line. In the initial stage elastic deformation occurred in the main rods and then, with increasing load, plastic deformation was noted. Deformation of the main stabilizer rods differed, and depended on the variant. In the first variant deformation occurred in the 2 major external rods which were pointing down. In the second variant the center rod was most affected. In configuration 3 the center rod bent upward, while the two extreme rods bent downwards. In a few cases, rupture of the screw mounting clip occurred. After modifications of the clips, further damage was not observed.

Statistical analysis results

1. Comparison of the mean value of maximum force obtained in three-point bending test using a bone stabilizer in 3 variants

	Numer of measurements	Mean force value [kN]	95% confidence limits
Group 1.	16	2.781	2.569-2.992
Group 2.	13	3.220	3.072-3.369
Group 3.	13	2.702	2.510-2.894

There was no evidence to reject the hypothesis of homogeneity of variance in the groups ($p=0.6765$).

The existence of a significant difference from the treatment group ($p=0.0005$) was confirmed.

The force required for the destruction of the bone fixation was significantly higher in Group 2 as com-

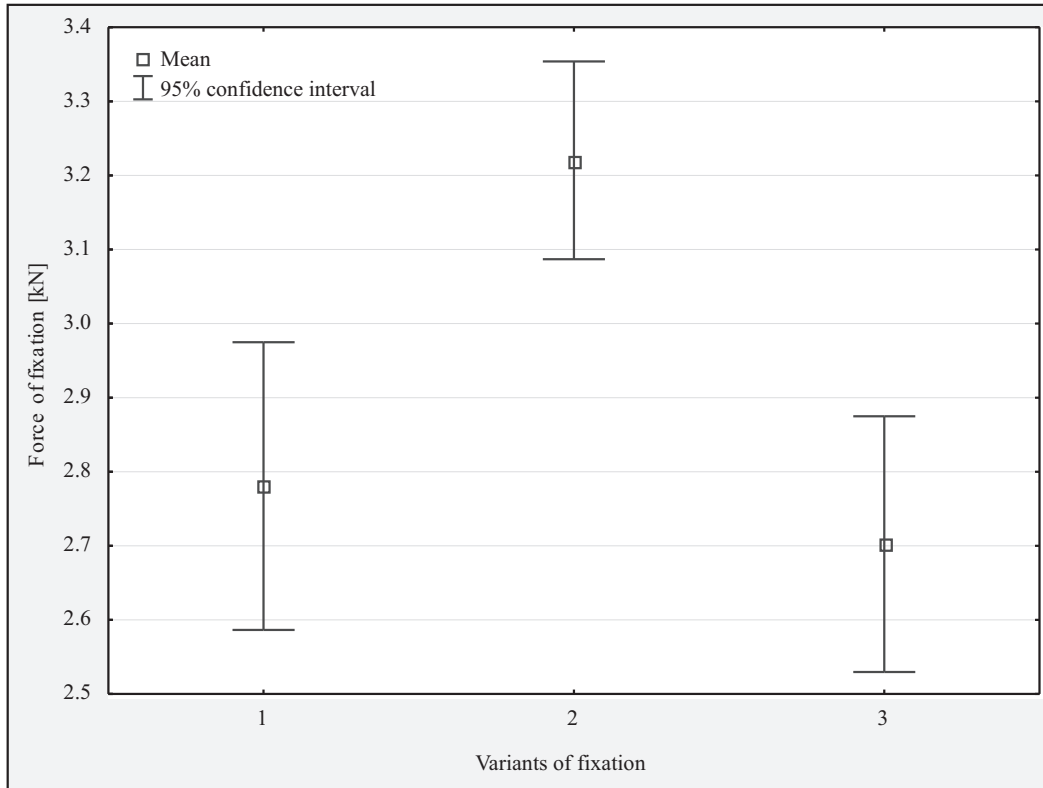


Fig. 4. Values of maximal force depending on the fixation variant.

pared to Group 1 ($p=0.0047$) and Group 3 ($p=0.0009$). There was no difference between Groups 1 and 3 ($p=0.8199$) (Fig. 4).

2. Determination of correlation between maximum force of fixed bones in three variants and cross-sectional field of diaphysis in one 1/2 lengths

A linear correlation between the maximum strength in 3 variants and their cross-sectional area was tested by calculating the Pearson correlation coefficient. The level of significance (α) was set at 0.05.

Results

	Number of bones	Pearson correlation coefficient R	Significance of correlation coefficient - p value
Variant 1.	16	0.2999	0.2591
Variant 2.	13	0.3626	0.2233
Variant 3.	13	-0.0075	0.9805

A linear correlation between the maximum force and cross-sectional area was not noted, regardless of the variant of the fixation.

Discussion

This study evaluates the fixation of diaphyseal fracture of metacarpal III in 1/2 length using an external stabilizer of our own design.

Notes on the construction of the stabilizer

In designing the stabilizer attention was paid to obtaining a structure of minimal weight and providing easy placement of implants in the bone in such a way that mobility in three planes of individual screw support elements was achieved. The three metal rods, each 200 mm long, which form a 3D structure were attached in the proximal and distal regions with the use of metal clamps (horseshoe shape) and 5 mm-diameter screws. The horseshoe shape ensures the proper distance from each of the main bars, which is just 80 mm. This allows easy screw attachment. The advantage of this solution is the substantial ease of placing more arms of implants along the fraction. Natural conditions, however, limit the possibility of increasing the number of implants. Therefore there is a need to optimize the use of their possible load. The loads are transferred between the section of the implant embedded in the bone and its holder. They cause bending moments $\pm Mg = F l/2$. These, in turn, cause stress, which cannot exceed the limit values. The only possibility of reducing these moments (and thus the stress) is shortening the length of the distance (L) between the bone and the screw clamp, which can be achieved by maximizing the proximity of the implant holder (clamp) to the bone (skin surface). In our stabilizer we added an additional joint in the screw

clamp, which allows maximum proximity to the skin surface and thereby shortens the loaded distance L of the implant.

The use of rods with a diameter of 8 mm instead of 10 mm allowed a significant reduction in the weight of the stabilizer without affecting its strength. Such a stabilizer is more flexible in comparison with the model using the 10 mm bars. The combination of three main stabilizer bars with horseshoe clamps is performed by the use of six M5 screws (3 for each horseshoe) screwed into a threaded portion of the rod. This method of fixing significantly simplifies and speeds installation.

Notes on material and methods

No bones were collected from horses younger than two years of age because the processes of bone growth are not yet completed in these animals and the bone is less strong due to the weakest place which is the epiphyseal cartilage. In setting the upper age limit, there were no bones collected from horses older than seven years of age in order to avoid the possible impact of advanced age on bone quality.

The study of bone pairs in which one is a control relative to the other, is consistent with the views of other authors (McClure et al. 1994, McClure et al. 1994b, McDuffee et al. 1994). The choice of which one of them was to be tested for compression and bending was random. Earlier studies on tibias derived from horses provide evidence that there is no statistically significant differences between the left and right bones (McDuffee et al., 1994).

Method of placing screws in the bone

Placing the screws in a tent style was important for maximizing strength of construction and bone fragment fixation was. This arrangement provides a much larger implant fixation strength than when set perpendicularly. The oblique screw orientation means that a larger portion of the implant is in the bone than it would be when set perpendicularly. Furthermore, the introduction of implants from the lateral or medial side is responsible for much larger bone-implant contact than with a dorsal approach. These differences arise from the considerable variation in the thickness of cortical bone, which is thickest on the dorsal, lateral and medial sides and thinnest on the palmar side. This means that the choice of screw placement is of significant importance. For greater strength, it is important that the fixation screw clamps are placed as close as possible to the bone but in such a way as not to dam-

age it (Ramotowski et al. 1988). The distance between bone and stabilizer provides elasticity, which is beneficial in the processes of bone healing (Ramotowski et al. 1988). Another advantage of this arrangement of implants is to minimize damage to important structures, such as tendons and ligaments.

Strength tests

1. Determination of maximum force for non-fractured bones

The mean values of the maximum force in the compression test, which are more than 67 kN, and almost 20 kN in the three-point bending test, show that the bone is relatively resistant to such forces. The large span of values obtained can attest to the fact that the bones of individual horses vary considerably. In addition, fractures occurred predominantly in the proximal part which is comprised mainly of cancellous bone.

2. Determination of maximum force for fractured bones fixed with stabilizer

a) compression test

Six right bones were used for this study. The left bones were used in the three-point bending test. Originally it was planned that the three-point bending test should be carried out on the left bones and compression test on the right. However, after carrying out the first six compression tests, the value of 25 kN was achieved and fixation was still stable. In order to avoid damage to the stabilizer, the test was stopped at this stage. After a thorough analysis, and removal of the stabilizers, no damage or abnormalities to the bone and stabilizer were observed. Considering the theoretical force that can occur during limb weight bearing, we come to the conclusion that the greatest weight bearing may occur during waking of the horse after surgery. Assuming the horse's body weight is 500 kg, and that 60% of the body weight falls on the thoracic limbs, we obtain a result close to 300 kg. Theoretically, it may thus happen that, during standing up after surgery, 60% of the weight will fall on one thoracic limb. This would mean that the stabilized III metacarpal bone would bear the force $F = 9.81 \text{ m/s}^2 \times 300 \text{ kg} = 2743 \text{ N}$. The force values obtained in the compression test were about 25kN (25000N), which means that they are ten times higher than those calculated theoretically. It seems that we need not fear the destruction of the stabilizer when the limb is weight bearing in a standing position by considering only the forces acting along the long axis of the bone. However, we must remember that during waking bending forces will work as well. Therefore, in the following studies only bending tests were performed on both bones

b) three-point bending test

The study was conducted in three variants, which differed between each other in quantity and distribution of screws in the bone.

Variant 1 – the mean value of maximal force obtained is 2.78 kN. Scatter of results was quite significant, ranging from 1.57 (min) to 3.44 (maximum).

Variant 2 – the mean value of maximal force obtained is 3.22 kN. In comparison with the first variant there is a slightly higher average value and less variation in the results. The minimum value is 2.62 kN and 3.62 kN maximum.

Variant 3 – mean value of maximal force obtained is 2.70 kN with a fairly large variation between a minimum value of 1.69 kN and a maximum of 4.03 kN.

These results, it suggest that the best option is variant 2.

Another question to be asked here is whether the mean force values are sufficient to avoid the destruction of the fixation during waking. The answer is yes, they are. The best option turned out to be variant 2 when the forces are greatest – around 3.22 kN. Theoretical considerations regarding the weight bearing that may arise during waking led us to the value of 2743 N, i.e. 2.74 kN. It is clear that the mean value obtained in the tests is much higher.

By analyzing adverse events, such as bending of the rods that occurred during the test, there may be other positive aspects. We know from experience that in the case of the use of plates, which are screwed into the bone, the structure is too stiff and there are problems with the healing of the bone (Ramotowski 1988). This rigidity is also not favorable for the bone, because it is easier to destroy it at the time of waking. The effect of diffraction (elastic deformation) that occurs during the test may be favorable, since it can protect the bone before it breaks. These deflections, which occur in various parts of the stabilizer, will prevent the bone from being destroyed and, which is more important, promote faster healing of bone fractures. A practical example is the fast bone union achieved in two cases treated by using the elements of the stabilizer described. The fact that breakage of screws and bone damage did not occur, is very important.

Assessment of the usefulness of the stabilizer in the treatment of fractures of the diaphyseal III metacarpal bone in horses

On the basis of the strength tests, we can conclude that the stabilizer can be strong enough to allow the horse to stand up after surgery. However, we do not know how the stabilizer will work during cyclic load-

ing. From our previous experience with the use of external fixators we believe that the main problem is osteolysis of bone around the most loaded implants, which appears after about 3 months. It is therefore a time when we can observe the characteristics of bone union.

The design of our external fixator has many advantages, as listed below:

Easy assembly and removal – installing the stabilizer requires the placement of 8-10 implants in bone and then combining them with the construction of the stabilizer. The use of self-tapping screws significantly reduces installation time. Removing the stabilizer and screws from the bone is very easy and fast. Worth emphasizing is the fact that general or local anesthesia is not necessary for this. In addition, tissue trauma associated with both the assembly and removal is small.

Another advantage is the ability to adjust the flexibility of the fixation by varying the distance of the stabilizer from the bone. Increased flexibility of the fracture fixation stimulates the production of abundant scar tissue and bone. Elastic deformation of the bars that was observed during the test influenced the healing process positively as well. The device is designed in such a way that it does not impede the normal functioning of the patient. The stabilizer is placed close to the body and additionally the dressing protects the opposite limb from damage. Furthermore, there is good access to the surgical site and wound care.

Providing good stabilization of bone fragments is not easy due to the distance between the stabilizer from the bone structure. Of greatest importance for the strength of the fracture is reducing the distance between the screw connector and the bone.

The stabilizer, after minor modifications, can also be used in the treatment of fractures of other bones. Furthermore, the individual elements of the stabilizer can be used in the treatment of selected fractures in horses as a one-side stabilizer. The author treated a tibia fracture in a 4-month-old foal in this way and a mandible fracture in an adult horse, in both cases successfully. The horse with the fractured mandible returned to show-jumping 3 months after surgery. The horse with a comminuted tibia fracture was able to move in all gaits (walk, trot and canter) by four months after the operation. By seven months after surgery he had joined other horses in the paddock. In 2013 he began his training at the racetrack in Służewiec.

Our stabilizer, as a 3D construction, is mainly used in the treatment of open or infected fractures when other methods of osteosynthesis cannot be used. Placing the implants at a greater distance from the

fracture line minimizes the risk of spreading infection. In many cases it is possible to mount a stabilizer in a closed way without the need for uncovering the fracture line.

Conclusions

1. The values of maximal force for broken bones and fixed bones with the use of this stabilizer show that the stabilization of the fracture using our own-designed stabilizer is sufficient to cope with the loads that may occur during the waking of a horse after surgery.

2. The second variant of placing the screws is most preferred in terms of strength.

3. It is possible to apply such a stabilizer in the treatment of transverse diaphyseal fractures of the III metacarpal bones in patients.

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