Original Article

Comparison of different pinning techniques for 3D-printed radius with Salter-Harris type I fracture

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Abstract

The purpose of the present study was to compare different pinning techniques for distal radius with Salter-Harris type I fracture. Computed Tomography (CT) images of a distal antebrachium of the 6.5 kg, growing, 6-month-old intact male mongrel dog were 3D-printed with Polycarbonate (PC) material. Twenty-one synthetic bones were classified into three groups. Cross pinning, Parallel pinning, and HK2 pinning techniques were applied to each group. A compressive shear test was applied to each group, and the results at 1 mm, 2 mm, and 3 mm displacement and the load at failure were analyzed through statistical software. It was found that there was no significant difference ($p = 0.156$) among the three groups at 1 mm displacement load. When comparing loads at 2 mm displacement, a significant difference ($p = 0.024$) was observed between the HK2 pinning group (224.6 ± 21.8 N) and the Parallel pinning group (188.1 ± 18.2 N). When comparing loads at 3 mm displacement, the HK2 pinning group (392.9 ± 35.6 N) and Cross pinning group (379.4 ± 37.6 N) showed significantly higher ($p = 0.006$, $p = 0.028$) loads than the Parallel pinning group (329.1 ± 25.1 N). In the comparison of maximum failure loads, a significant difference ($p = 0.029$) was observed between the HK2 pinning group (546.6 ± 47.5 N) and the Parallel pinning group (478.6 ± 44.3 N). In conclusions, the reduction of the distal radius with Salter-Harris type I fractures using the novel HK2 pinning technique in 3D-printed bones was similar or superior to other pinning techniques.

Keywords: canine, radius, Salter-Harris fracture, pinning, polycarbonate

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Introduction

In dogs, the radius is the most weight-bearing bone in the forelimbs. Statistically, fractures of the radius account for 36.5% of all fractures and 43.1% of long bone fractures (Popovitch *et al*., 2019). In most forearm fractures, it is reported that the distal third of the antebrachium is mainly affected there is relatively little soft tissue (Muir, 1997). Similarly, in growing puppies, 30% of distal radius fractures are reported to affect physis because a physis is composed predominantly of cartilage that is mechanically weaker than adjacent ossified bone (Meakin and Langley-Hobbs, 2016). In addition, the growth plates of the distal fragment and ulna have a curved shape, making them vulnerable to trauma (Woods and Perry, 2017). Statistically, 39% of physeal fractures in dogs and cats were Salter-Harris Type 1 fractures (Engel and Kneiss, 2014). Salter-Harris type 1 fractures are usually the result of a shearing force (Dover and Kiely, 2015).

There are conservative techniques and invasive surgical techniques to treat growth plate fractures. The conservative technique is a method of non-surgical closed reduction followed by casting or bandage. Closed reduction is difficult and limited in that it can be applied only within 24–48 hours after trauma, and accurate reduction is challenging. One study found that displacement was induced in 75% of cases after closed reduction and severe non-union in 25% of cases. On the other hand, in invasive surgical treatment, an accurate reduction is possible, there is less displacement after reduction, and the rate of non-union and premature closure of the growth plate is reduced (Hudson *et al*., 2020).

Currently, the gold standard for treating growth plate fractures are the cross pinning and parallel pinning techniques. Also, external skeletal fixation (ESF) techniques are widely applied. Those internal fixation techniques and external fixation techniques using K-wire can be applied to dogs of all sizes (Rogge *et al*., 2002). Previous studies on the Cross pinning and the Parallel pinning techniques showed a variable pin removal rate after the reduction of physeal fractures. A study reported that the pin migration rate was 4% and pin removal due to irritation was 41% (Boekhout *et al*., 2017).

Otherwise, intramedullary pins should be prohibited because they have growth-related side effects in 80% of cases. The plate used for most long bone fractures can also be applied, and it is advantageous in situations such as complex fractures or postoperative non-union (Popovitch *et al*., 2019).

As mentioned above, various surgical techniques using K-wire have been studied and applied. However, comparative studies between the novel HK2 pinning method with multiple advantages and conventional surgical techniques have yet to be conducted. Therefore, the hypothesis of this study is that the HK2 pinning technique will be resistant to shear load like conventional golden-standard techniques. And the purpose of the study is to conduct a comparative biomechanical study of cross pinning, parallel pinning, and HK2 pinning techniques applied to synthetic bone.

Materials and Methods

Subject preparation: The computed tomography (CT) image data of a 6.5kg, growing, 6-month-old, intact male mongrel dog was used. The dog had previously undergone a CT scan for fallen trauma on an opposite limb. The CT image was customized using Custom-Medi® (Custom-Medi corporation, Daejeon, Republic of Korea). CT image data processing was performed with a slicer program (3D slicer v1.0, http://www.slicer.org). Modeling was processed using the 3Ds Max program (3Ds Max 2019, Autodesk Inc., California, MV, USA).

A square base is printed at the end of the bone to facilitate angle maintenance and fixation (Fig. 1). The angle of bone and base was set by referring to the maximum extension carpal angle when landing after jumping (Castilla *et al*., 2020, Neville *et al*., 2018). Polycarbonate (PC) was selected as the material because of its lighter weight and lower Young's modulus than actual bone, it has been found to have very similar compressive strength and fracture stiffness to bone per volume (Mantripragada *et al*., 2013). A total of twenty-one synthetic bones were printed and distributed to three groups: Cross pinning, Parallel pinning, and HK2 pinning. The 1.2 mm diameter K-wire was used for surgical pinning techniques, mainly selected for physeal fractures of medium to large breed dogs, and the smallest size suggested by AREX® (HK2®, AREX Inc., Palaiseau, CT, France).

Surgical procedures:

Cross pinning: The first 1.2 mm K-wire was driven from the medial surface of the radial styloid process, angled to be at 30 degrees to the sagittal plane, and anchored in the lateral cortical bone of fragmented distal bone. The second K-wire was driven from the lateral side of the ulna styloid process, angled to be at 30 degrees to the sagittal plane, and anchored in the medial cortical bone of the proximal fragment. It is contraindicated for the intersection point to be located on the fracture line, so the two pins had to be crossed proximal to the growth plate (Hudson *et al*., 2020) (Fig. 2A).

Parallel pinning: The first 1.2 mm K-wire was driven from the cranial surface of the distal fragment, angled at 90 degrees to the growth plate and at 30 degrees to the transverse plane and anchored in the caudal surface of the proximal fragment. The second pin was applied similarly but parallel to the first one (Fig. 2B).

HK2 pinning: HK2 is based on an ESF type 1b principle with bi-planar half-pins (Fig. 2C). First, the following describes a method for the intrafocal pin applied to the proximal fragment. A 1.2 mm K-wire was driven from the medial side of the proximal fragment, above the growth plate line, angled at 45 degrees to the long axis (Fig. 3A). The following describes a method for the distal pin applied to the distal fragment. Considering the position and direction of the intrafocal pin, the distal pin was driven into the distal fragment parallel to the growth plate (Fig. 3B). The intrafocal pin was bent at the point where it came out of the skin and angled at 90 angles to the long axis. After passing the intrafocal pin and distal pin through the crimp, the reduction of the growth plate and the alignment of the pins were confirmed using a radiograph. Then the crimp was rigidly fixed close to the bend of the intrafocal pin (Fig. 3C). Similarly, pins were driven and set on the lateral surface of the radius (Fig. 3D). And the two planes of four pins were not parallel, taking into account the direction of the shear load (Maire *et al.*, 2013).

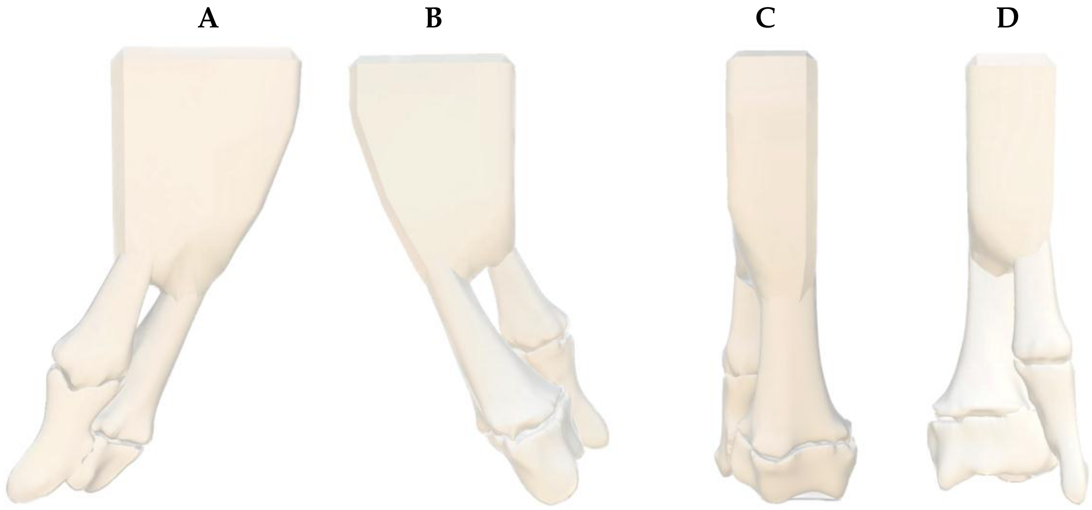

Figure 1 A 3D-model of canine antebrachium with square base.
A: Lateral view, B: medial view, C: Cranial view, D: caudal view
The angled square base is printed with the bone model.

Figure 2 Schemes of the pinning techniques.
A: Cross pinning. B: Parallel pinning. C: HK2 pinning.
The Cross pinning technique and the Parallel pinning technique are conventional golden-standard techniques for radius with Salter-Harris type 1 fracture.

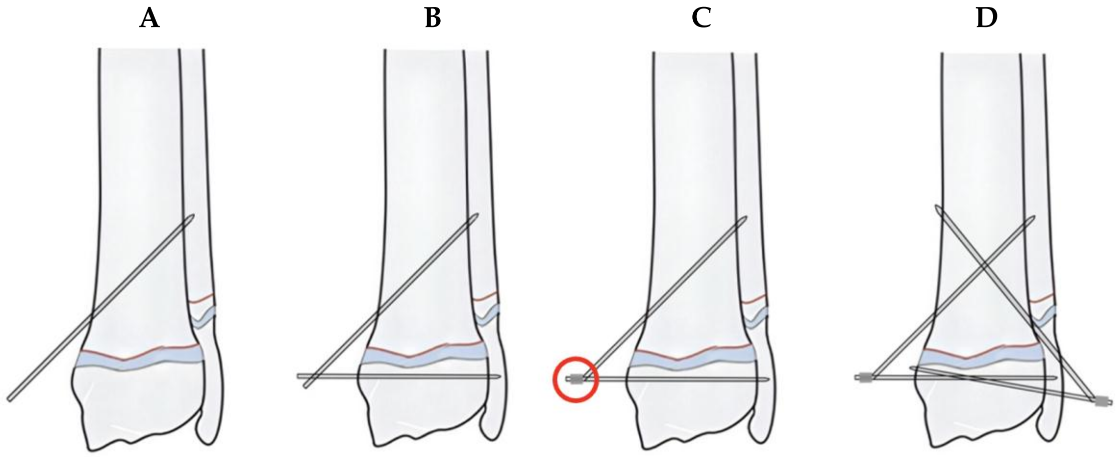

Figure 3 Schemes of process of HK2 pinning techniques.
A: Intrafocal pin. B: Distal pin. C: Bending and crimping. D: Bi-planar application
The pins are applied in the manner of external skeletal fixation type 1b.

Biomechanical test: In this study, the bone and base were printed at an angle to induce a shear force. In the previous research, most of the Salter-Harris type 1 fractures were caused by shear forces (Sukhiani and Holmberg, 1997). Then the biomechanical test was performed by shear compressing the distal fragment in the direction of the landing force after a hurdle jump using a universal testing machine (Intron 4467®; INSTRON Inc., Norwood, MA, USA). The loading speed was 5mm/min, and the sampling rate was at 10 ms intervals.

Statistical analysis: Statistical analysis of the results was performed using the SPSS program (SPSS v25.0.0, IBM SPSS Corporation, Chicago, IL, USA). The Shapiro-Wilk test of all groups confirmed normal distribution at all displacements and maximum failure ($p > 0.05$). Using Levene's test, the equality of variance was confirmed for all groups at all displacement and maximum failure ($p > 0.05$). Using a One-way ANOVA comparison, it was confirmed that there were no significant differences between the three groups at all displacement and maximum failure ($p < 0.015$). The post-hoc Turkey HSD test confirmed significant differences between groups ($p < 0.05$).

Results

Loads at 1 mm displacement: The mean loads of each group at 1 mm displacement were 111.7 ± 13.2 N in the Cross pinning group, 98.3 ± 9.5 N in the Parallel pinning group, 111.1 ± 17.8 N in the HK2 pinning group (Table 1).

Loads at 2 mm displacement: The mean loads of each group at 2 mm displacement were 216.1 ± 21.9 N in the cross pinning group, 188.1 ± 18.2 N in the Parallel pinning group, and 224.6 ± 21.8 N in the HK2 pinning group (Table 1).

Loads at 3 mm displacement: The mean loads of each group at 1 mm displacement were 379.4 ± 37.6 N in Cross pinning group, 329.1 ± 25.1 N in the Parallel pinning group, and 392.9 ± 35.6 N in the HK2 pinning group (Table 1).

Maximum failure loads and failure mode: The mean loads of each group at maximum failure loads were 529.0 ± 43.0 N in Cross pinning group, 478.6 ± 44.3 N in the Parallel pinning group, and 546.6 ± 47.5 N in the HK2 pinning group (Table 1). The failures were observed and recorded during the biomechanical tests. In all groups, all samples failed due to fractures of the bone around the pins.

Table 1 Loads (N) at 1 mm, 2 mm, and 3 mm displacement and the maximum failure

Displacement	Groups		
	Cross pinning	Parallel pinning	HK2 pinning
1 mm	111.7 ± 13.2[a]	98.3 ± 9.5[a]	111.1 ± 17.8[a]
2 mm	216.1 ± 21.9[ab]	188.1 ± 18.2[b]	224.6 ± 21.8[a]
3 mm	379.4 ± 37.6[a]	329.1 ± 25.1[b]	392.9 ± 35.6[a]
Maximum failure	529.0 ± 43.0[ab]	478.6 ± 44.3[b]	546.6 ± 47.5[a]

Statistically significant differences were shown among the three groups ($p < 0.05$). Significant differences are indicated by measurements having different superscript letters (a, b). (E.g., The superscript "a" and "ab" are not significantly different because they share a common superscript.)

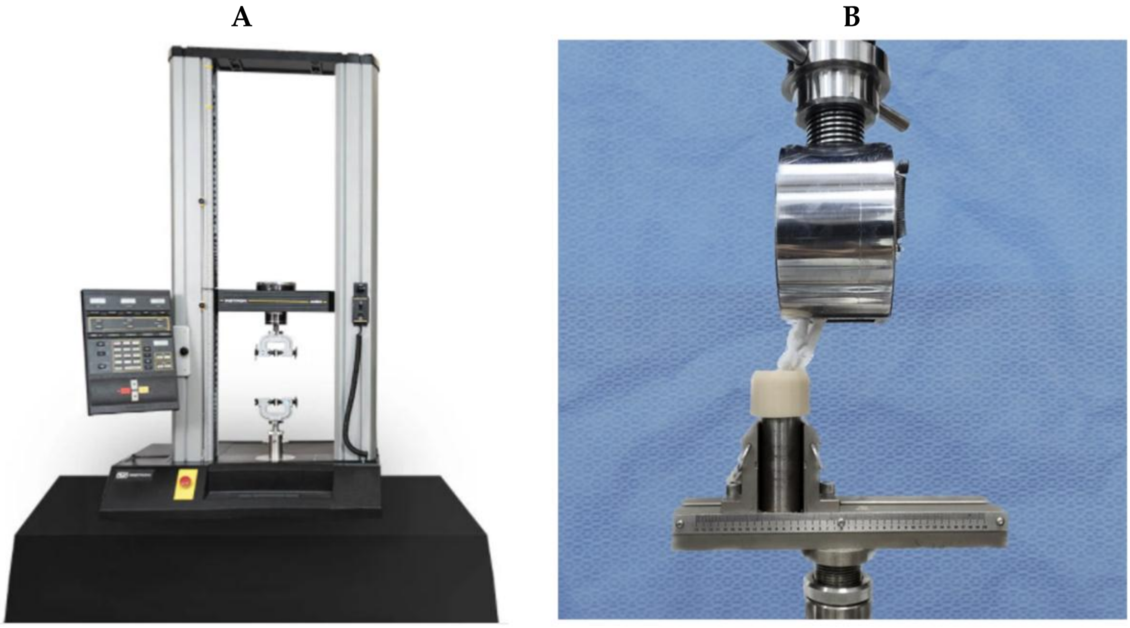

Figure 4 Biomechanical shear force testing.
A: Universal testing machine, B: Biomechanical test set
A shear force angle mimics the physiological angle during landing after a jump.

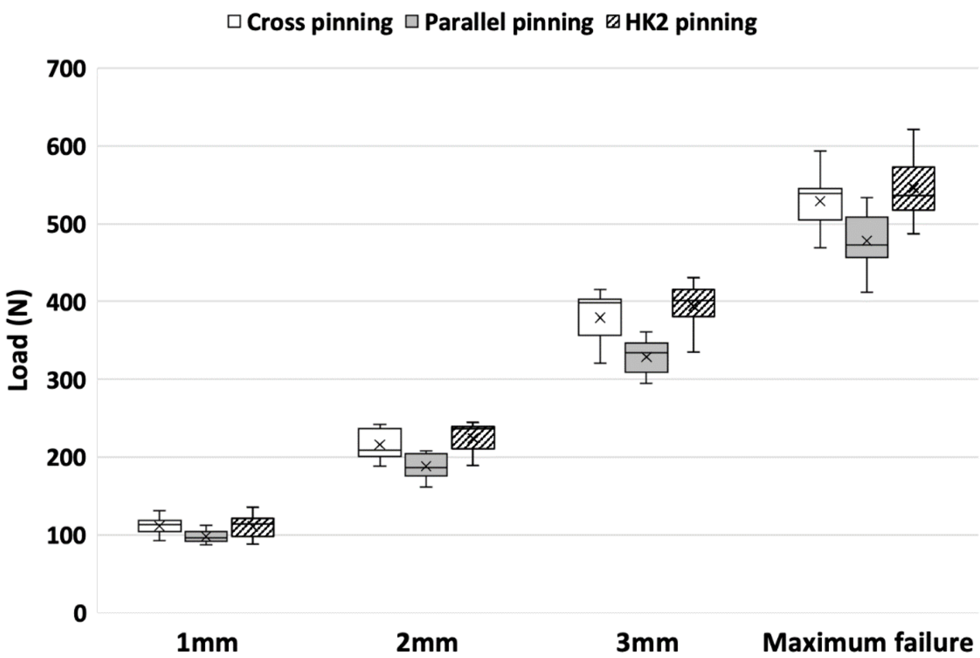

Figure 5 Box-whisker plot of loads at 1 mm, 2 mm, and 3 mm displacement and maximum failures.
The top and bottom edges of the box plot indicate the first and third quartiles. The line indicates the median. The cross indicates the mean. The whiskers extend to 150% of the interquartile range. Statistically significant differences were shown among the three groups ($p < 0.05$). Statistically significant differences ($p < 0.05$) are indicated by measurements having different superscript letters (a, b). (E.g., The superscript "a" and "ab" is not significantly different because they share a common superscript.)

Discussion

The HK2 pinning technique is based on the ESF type 1b system and has the advantages of not directly penetrating the growth plate, distributing the compression force applied to the fracture surface, and not damaging soft tissue during removal. In this study, HK2 was compared with the Cross pinning technique and the Parallel pinning technique, Golden-standard techniques. HK2 showed superior results compared to the conventional golden-standard techniques.

In-vitro bones, even when used as matched pairs, vary in shape, size, age, and density. Therefore, in-vitro bones cannot be considered as a uniform test medium. Recently, the evaluation of fixation methods using 3D-printed bone has been universally performed. The 3D-printed bone can reduce many variables compared to cadaver bone. If the variables are controlled, the results of the comparison can be considered sufficiently significant (Hausmann, 2006). Furthermore, in this study, an accurate Salter-Harris type 1 fracture model was feasible by printing the curved shape of the growth plate.

Comparing loads at 1 mm displacement, no statistically significant (p = 0.156) differences were found among the three groups. This can be analyzed as a combination of the low Young's modulus of the polycarbonate material and the resistance from surgical prostheses. Comparing loads at 2 mm displacement, There were significant differences among the three groups. The HK2 pinning group performed at 18% higher resistance than the Parallel pinning group, and a statistically significant difference was also confirmed (p = 0.024). Comparing loads at 3 mm displacement, There were significant differences among the three groups. The HK2 pinning group performed at 18% higher resistance than the Parallel pinning group, and a statistically significant difference was also confirmed (p = 0.006). The Cross pinning group performed at 15% higher resistance than the Parallel pinning group, and a statistically significant difference was also confirmed (p = 0.028). Comparing maximum failure loads, There were significant differences among the three groups. The HK2 pinning performed at 14% higher resistance than the parallel pinning and a statistically significant difference was also confirmed (p = 0.029). The Cross pinning group showed a 10% higher mean load than the Parallel pinning group, but statistically, a significant difference was not found. The HK2 pinning group performed about a 14% higher mean load than the Parallel pinning group, and a significant difference was confirmed. The ratios of the difference in the mean loads among each group at maximum failure decreased compared to ratios at the 2 mm or 3 mm displacement due to the fracture of the synthetic bone near pins, not the failure of the prostheses. Because the synthetic bone had a thin shell (Cortical part) that printed similarly to the 6-month-old puppy, this was similar to the failure pattern that appeared in the existing biomechanical studies that applied pinning techniques to skeletally immature dogs (Sukhiani and Holmberg, 1997). There was no significant difference between the Cross pinning group and the HK2 pinning group.

Referring to previous studies and literature, displacement under 1 mm was defined as a change that could cause minimal malunion, a 1-3 mm displacement as a change that could cause moderate displacement, and 3 mm as a change that could cause severe malunion (Boekhout *et al*., 2017). In other studies, the displacement under 2 mm after surgical reduction was acceptable (Crawford, 2012, Barmada *et al*., 2003).

The analysis by surgical technique is as follows. The cross pinning technique is the most preferred and the golden-standard technique for growth plate fractures. Compared to the parallel pinning group, the cross pinning group performed at a 14% higher mean load at 2 mm displacement but a significant difference was not found. Comparing at 3 mm displacement, a 15% higher mean load was performed and a significant difference was confirmed. The parallel pinning group performed the weakest resistance to displacement and failure. According to previous studies, the parallel pinning technique was more unstable than the cross pinning technique but it is more advantageous for the continuous growth of the physis, so it is the recommended surgical method for dogs under 5-months-old (Culvenor *et al*., 1996). The HK2 pinning technique was recently developed in human medicine and applied to patients of various ages for fractures of the radius and ulna. It has many advantages compared to conventional trans-physeal pinning techniques. Compared with the parallel pinning group, it performed at a 18% higher mean load at 2 mm displacement and about a 19% higher mean load at 3 mm displacement and a significant difference was also confirmed.

The various vertical ground reaction loads based on previous studies are as follows; walk (6.5 N/kg), trot (10.4 N/kg), and hurdle jump (45 N/kg) (Oosterlinck *et al*., 2010, Pfau *et al*., 2011). All the surgical methods were able to withstand the one-time walk and trot. However, the hurdle jump is a force that can induce a displacement of 2-3 mm for all surgical techniques. As the displacement exceeds 2 mm, the potential for nonunion and premature closure of the physis might increase (Crawford, 2012). Therefore, the resistance force of all three groups stably endured a single standing and trot, but the treatment of the physis could be unstable in an active situation. However, as in clinical situations, additional adjuvant treatment methods such as bandages or casts should be added to the fixation technique, resulting in better outcomes and prognosis (Rogge *et al*., 2002).

Because physeal fractures of young animals heal quickly, most physeal fractures have 8-10 points of fracture scores. Ideally, after the reduction of growth plate fracture, primary healing should be occurred to continue growth. This must be supported by rigid and stable fixation after accurate reduction. If rigid and stable fixation is maintained, the initial angiogenesis of metaphyseal vessels across the fracture line gap will be induced and repaired through a continuation of normal endochondral ossification. If movement or displacement is severe because fixation is not rigid and stable, fibrous tissue is formed in the fracture line, and vascular invasion will be unable to cross the separation gap. In this situation, fibrous tissue callus is deposited initially to increase fracture gap stability, and then vascular ingrowth and restoration of normal endochondral ossification will be induced (Ma *et al*., 2017).

Until recently, comparative studies on various fixation methods for physeal fractures have been conducted. However, most of the previously used pinning methods were applied by penetrating the physis and complications from the pin had been reported. Injury to the physis often stimulates bone repair, leading to limb length discrepancy, bone bridge formation between the metaphysis and epiphysis and angulation of the bone. The incidence of bone bar formation by the pinning process has been approximately 7-9% in rabbit studies (Dahl *et al*., 2014). It can be induced and can be peripheral, elongated or central to the bone. Whereas central bars are more likely to result in limb length discrepancy, peripheral or elongated bars can result in angular deformity of the bone. In human medicine, bone bar resection surgery has become an accepted treatment option for patients with developing deformities (Khoshhal and Kiefer, 2005).

In addition, conventional pinning surgery techniques involve bending and cutting the tip of the pin to bury it under the skin. Damages to soft tissues during the pinning process are usually occurred by bending the pin rather than penetrating (Harari, 1992). In addition, growing bones are weak, which can cause additional bone damage during the cutting and bending process (Popovitch *et al*., 2019).. The HK2 pinning technique has various biological advantages. First, pins of the HK2 pinning techniques do not directly penetrate the physis, so that it can prevent bone bar formation. Since the HK2 pinning technique is an ESF system, there is no need to cut the pins short as the pins come out of the skin (Maire *et al*., 2013). In addition, when the pins are removed after 4-6 weeks of treatment, a tissue isolation process is not required as they are removed from the outside of the skin (Camus and Van, 2018). One of the disadvantages of standard smooth pins is that pins can become loosened or diverge. On the other hand, the HK2 pinning technique resists pullout force itself without additional external coaptation. According to a study in human medicine, the HK2 pinning technique solved the loosening problem of existing pins and reduced the infection rate to nearly 0%. Even in bones with osteolysis, the pins were immobilized (Camus and Van, 2018). The basic principle of HK2 pinning is the bridging system. A compression force applied to the epiphysis is transmitted and distributed from the distal pin through the crimp to the intrafocal pin. Tightly tightened crimps play an important role as a force transmission point (Camus and Van, 2018).

The limitations of this study are as follows. First, the number of samples is small. Second, the experimental material and process did not fully reflect the mechanism of the canine antebrachium. In addition, the failure to proceed with an evaluation of flexion and extension exercise or repetition test was also set as a limitation. Better results and prognosis will be obtained if additional adjuvant treatments such as bandages or casts are combined with the procedures. Based on this study, further research in in-vitro or pre-clinical in-vivo is needed. The compression test was only performed on the radial Salter-Harris type 1 fracture, but application to other fractures or other bones is also necessary. In addition, A tensile force test should also be performed in various fractures.

In conclusions, application of the novel HK2 pinning technique in a 3D-printed distal radius with Salter-Harris type 1 fracture was superior to conventional golden-standard techniques. In addition, the HK2 pinning technique has advantages, compared with conventional techniques.

References

Barmada A, Gaynor T and Mubarak SJ 2003. Premature physeal closure following distal tibia physeal fractures: A new radiographic predictor. Journal of Pediatric Orthopaedics, 23(6), 733-739.

Boekhout TCL, Kim SE, Cross AR, Evans R and Pozzi A 2017. Closed reduction and fluoroscopic-assisted percutaneous pinning of 42 physeal fractures in 37 dogs and 4 cats. Veterinary Surgery, 46(1), 103-110.

Camus EJ and Van OL 2018. Treatment of the distal radius fractures with percutaneous pinning: Evolution to the HK2 system. European Journal of Orthopaedic Surgery Traumatology, 28(8), 1477-1485.

Castilla A, Knotek B, Vitt M and Gordon-Evans W 2020. Carpal Extension Angles in Agility Dogs Exiting the A-Frame and Hurdle Jumps. Veterinary and Comparative Orthopaedics and Traumatology, 33(02), 142-146.

Crawford AH 2012. Triplane and Tillaux fractures: Is a 2 mm residual gap acceptable?. Journal of Pediatric Orthopaedics, 32, S69-S73.

Culvenor JA, Black A, Lorkin KF and Bradley WA 1996. Repair of femoral capital physeal injuries in cats-14 cases. Veterinary and Comparative Orthopaedics and Traumatology, 9(04), 182-185.

Dahl WJ, Silva S and Vanderhave KL 2014. Distal femoral physeal fixation: Are smooth pins really safe?. Journal of Pediatric Orthopaedics, 34(2), 134-138.

Dover C and Kiely N 2015. Growth plate injuries and management. Orthopaedics and Trauma, 29(4), 261-267.

Engel E and Kneiss S 2014. Salter-harris fractures in dogs and cats considering problems in radiological reports-a retrospective analysis of 245 cases between 1997 and 2012. Berliner und Munchener Tierarztliche Wochenschrift, 127, 77-83.

John W, Evans HE and De LA 2013. Bones of the Thoracic Limbs. Miller's anatomy of the dog-E-Book. Elsevier health sciences 123-136.

Harari J 1992. Complications of external skeletal fixation. Veterinary Clinics of North America: Small Animal Practice, 22(1), 99-107.

Hausmann JT 2006. Sawbones in biomechanical settings-a review. Osteosynthesis and trauma care, 14(04), 259-264.

Hudson CC, Kim SE and Pozzi A 2020. Percutaneous pinning for fracture repair in dogs and cats. Veterinary Clinics: Small Animal Practice, 50(1), 101-121, 963-974.

Johnson AL, Houlton JE and Vannini R 2005. Fracture of radius. AO principles of fracture management in the dog and cat. Georg Thieme Verlag, 253-258.

Khoshhal KI and Kiefer GN 2005. Physeal bridge resection. JAAOS-Journal of the American Academy of Orthopaedic Surgeons, 13(1), 47-58.

Ma J, Wang T, Lovric V, Johnson KA and Walsh WR 2017. A biomechanical comparison of Kirschner-wire fixation on fracture stability in Salter-Harris type I fractures of the proximal humeral physis in a porcine cadaveric model. BMC veterinary research, 13(1), 1-10.

Maire N, Lebailly F, Zemirline A, Hariri A, Facca S and Liverneaux P 2013. Prospective continuous study comparing intrafocal cross-pinning HK2® with a locking plate in distal radius fracture fixation. Chirurgie de la Main, 32(1), 17-24.

Mantripragada VP, Lecka-Czernik B, Ebraheim NA and Jayasuriya, AC 2013. An overview of recent advances in designing orthopedic and craniofacial implants. Journal of biomedical materials research Part A, 101(11), 3349-3364.

Meakin L and Langley-Hobbs S 2016. Physeal fractures in immature cats and dogs: Part 1–forelimbs. Vet Times. February, 15, 2016.

Michael R, Gayle H, Tobias KM and Tillson DM 2018. Bone Biomechanics and Fracture Biology, Radius and Ulna. Veterinary surgery: small animal. 2nd ed. St Louis: Elsevier Inc, 613-649,691-930.

Muir P 1997. Distal antebrachial fractures in toy-breed dogs. Compendium on continuing education for the practicing veterinarian, 19(2), 137-145.

Neville-Towle JD, Tan CJ, Parr WC, Walsh WR and Johnson KA 2018. Three-dimensional kinematics of the canine carpal bones imaged with computed tomography after ex vivo axial limb loading and palmar ligament transection. Veterinary Surgery, 47(6), 861-871.

Oosterlinck M, Pille F, Huppes T, Gasthuys F and Back W 2010. Comparison of pressure plate and force plate gait kinetics in sound Warmbloods at walk and trot. The Veterinary Journal, 186(3), 347-351.

Pfau T, Rivaz AG, Brighton S and Weller R 2011. Kinetics of jump landing in agility dogs. The Veterinary Journal, 190(2), 278-283.

Popovitch C, Gibson TW and Sylvestre AM 2019. Radius and Ulna. Fracture Management for the Small Animal Practitioner, 105-117, 245-248.

Rogge RD, Adams BD and Goel VK 2002. An analysis of bone stresses and fixation stability using a finite element model of simulated distal radius fractures. The Journal of hand surgery, 27(1), 86-92.

Woods S and Perry KL 2017. Fractures of the radius and ulna. Companion Animal, 22(11), 670-680.

Schulz KS, Hayashi K and Fossum TW 2018. Management of Specific Fractures. Small animal surgery e-book. Elsevier Health Sciences, 1077-1086.

Sukhiani HR and Holmberg DL 1997. Ex vivo biomechanical comparison of pin fixation techniques for canine distal femoral physeal fractures. Veterinary Surgery, 26(5), 398-407.