Biomechanical testing of a hybrid locking plate fixation of equine sesamoid osteotomies

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Keywords
Mid-body fracture, proximal sesamoid bone, locking compression plate, biomechanics, horses

Summary
Objective: To compare the biomechanical properties of a hybrid locking compression plate (LCP) construct with the compression screw technique as a treatment for transverse mid-body proximal sesamoid bone fractures.

Methods: Ten paired forelimbs from abattoir horses were used. The medial proximal sesamoid bone of each limb was osteotomized transversely and randomly assigned, to either repair with a two-hole 3.5 mm LCP or a 4.5 mm cortical screw placed in lag fashion. Each limb was tested biomechanically by axial loading in single cycle until failure. The point of failure was evaluated from the load-displacement curves. Then a gross evaluation and radiographs were performed to identify the mode of failure.

Results: The loads to failure of limbs repaired with the hybrid LCP construct (4968 N ± 2167) and the limbs repaired with the screw technique (3009 N ± 1091) were significantly different (p <0.01). The most common mode of failure was through a comminuted fracture of the apical fragment of the proximal sesamoid bone. Clinical significance: The LCP technique has potential to achieve a better fracture stability and healing when applied to mid-body fractures of the proximal sesamoid bone. Further testing, particularly fatigue resistance is required to corroborate its potential as a treatment option for mid-body fractures of the proximal sesamoid bone.

Introduction
Fractures of the proximal sesamoid bone are common in racing Thoroughbred and Standardbred horses. The risk of fatality during racing for Thoroughbred horses has been reported worldwide and varies between 0.33 and 1.7 horses per 1000 starts (1, 2). Of these, the most common musculoskeletal injury reported is fracture of the proximal sesamoid bone, followed by suspensory apparatus and third metacarpal bone injuries (3, 4). In a study of horses that died or were euthanatized on authorized Thoroughbred racetracks in California, 45% of them had at least one of the sesamoids fractured in the forelimbs and 28% had a mid-body type fracture (5).

The prognosis for horses with proximal sesamoid bone fractures varies according to the fracture configuration and method of treatment. Uniaxial mid-body fractures are typically treated surgically by two main methods although less than 50% of horses return to their previous level of racing (6, 7). Interfragmentary screw fixation in lag fashion and circumferential wiring are the two main techniques described to repair mid-body proximal sesamoid bone fractures. Comparisons of these two techniques showed that 44% of horses treated with screw repair raced after surgery whereas none of the horses with wire fixation raced (7). On the other hand, another retrospective study of repairs using the wire technique, showed that five out of 15 horses returned to their prior level of racing (8). Both of these techniques have limitations in their ability to obtain and to maintain fracture reduction, creating an interfragmentary gap that can result in excessive motion and a weak fibrous union (7).

Headless tapered screws, allogeneic bone screws, cortical bone screws, cerclage wires and polyethylene cables have all been tested biomechanically in a single cycle test as a fixation method for mid-body proximal sesamoid bone osteotomies (9–13). The results for the load at the failure point varied from 600 Newtons (N) to 6000 N with a wide individual variation (9–13). Around 9500 N of force was needed to break normal intact equine suspensory apparatus in vitro; this force was reduced to around 6200 N when the proximal sesamoid bone was osteotomized and repaired with a cortical screw (10). In another comparative study between screw and wire techniques, the mean load at failure of both repair methods was 3000 N (9).

The amount of tensile force applied to the proximal sesamoid bone fragments through the suspensory ligament and the distal sesamoidean ligaments can lead to gap formation and secondary implant failure. It has been established previously that
surgical plates are strong in tension (14). Using this principle, the objective of this pilot study was to test the biomechanical properties of a hybrid locking plate fixation as a treatment for transverse mid-body proximal sesamoid bone fractures and compare it with the standard cortical lag screw technique in a single cycle to failure. Our hypothesis was that the plate fixation construct would be stronger than the screw fixation construct in the biomechanical test under axial loading.

Materials and methods

Study design

A simulated mid-body transverse fracture was created in the medial proximal sesamoid bone by osteotomy in 10 paired forelimbs with an intact suspensory apparatus. One of the limbs was randomly assigned to the single screw technique and the other to a hybrid locking plate technique. The specimens were tested until failure in a single cycle of axial compression of the limb. The load-displacement curves were analysed to determine the load at failure. A gross evaluation of the limb and radiographs were compared before and after testing.

Specimen preparation

Ten fresh paired forelimbs were collected from abattoir horses of unknown age, breed, and gender. The specimens were harvested by transection at the distal radius and stored at −20°C until preparation. Twenty-four hours before preparation, the legs were thawed at room temperature. They were disarticulated at the middle carpal joint and the skin and superficial and deep digital flexor tendons were removed, leaving the suspensory apparatus intact. The limbs were checked for evidence of gross pathology of the suspensory apparatus by palpation and visual observation. Limbs were discarded if gross pathology or obvious limb deformations were present.

For all specimens, a 2 cm medial palmar arthroty of the metacarpophalangeal joint was performed to allow the observation of the proximal sesamoid bone during osteotomy and bone repair. Once the proximal and distal borders of the proximal sesamoid bone were identified using palpation and direct observation, the midpoint of the bone was identified using a ruler and a transverse mid-body osteotomy was performed. The osteotomy was made with a small oscillating bone saw and a saw blade, taking care to minimize damage to surrounding soft tissues and to not touch the lateral sesamoid bone.

Sesamoid bone repair technique

All limbs were repaired by the same surgeon (EAS). A single 4.5 mm cortical bone screw was placed in lag fashion in a distal to proximal direction across the osteotomy site as previously described (6, 15, 16). This served as the control group. The contralateral limb was assigned to the test group with a 3.5 mm two-hole locking compression plate, which was applied with a hybrid technique. The osteotomy was reduced with bone reduction forceps and the plate was placed on the abaxial surface of the osteotomized sesamoid. The plate was not conformed to the bone. A 3.5 mm cortical screw was placed in a neutral position in the distal hole through a 2.5 mm hole drilled in the basilar fragment, parallel to the fracture line. A 3.5 mm self-tapping locking head screw was placed in the proximal hole through a 2.8 mm hole drilled in the apical fragment parallel to the fracture line (Figure 1). The plate was placed just palmar to the origin of the dorsal branch of the suspensory ligament and every screw was tightened to a perceived maximum torque by hand. After the osteotomy reconstructions, the limbs were kept at 4°C in saline-soaked towels overnight until biomechanical testing the following day.

Mechanical testing

Each limb was placed in a servo-hydraulic machine by fixing the proximal end of the metacarpal bone and distal row of the carpus in an aluminium frame using polyester resin. The hoof was placed on a support designed to allow metacarpophalangeal joint flexion while preventing the hoof from sliding off the load machine. An initial axial load of 500 N was applied to stabilize the specimen on the testing machine. The axial compression load was applied in a single cycle at a rate of 4 cm/s until specimen failure, similar to the protocol used in a previous study (10). Load and displacement were recorded at 256 Hz using a 15 Kn load cell. The angle of dorsiflexion in the limbs was measured after the initial load and after the test with a protractor centred in the condylar fossa of the distal end of the third metacarpal bone to ensure that the biomechanical forces were not changed by limb position.

Failure analysis

Video images were recorded for each limb tested and analysed together with the load-displacement curve to determine the failure point. This point was defined as the first major discontinuity (sudden decrease) in the load-displacement curve. Gross evaluation and comparison between pre- and post-test radiographic images (lateral-medial and dorso-palmar views) were used to determine the mode of failure.

Statistical analysis

Limb were only compared within each set of paired forelimbs. No comparisons were made between sets of limbs on account of the variation in age, gender and size between samples. The paired Student’s t-test was used to compare the mean values for load, displacement and metacarpophalangeal joint flexion. The statistical analysis was carried out with a commercial software program and the level of statistical significance was set at 0.05. A power analysis was performed using the results of the first four limbs to determine the number of limbs required to give a power greater than 0.80.

References

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b Rayhack*: Microaire, Charlottesville, VA, USA
c Synthes Vet, West Chester, PA, USA
d 858 MiniBionix® II: MTS Systems Corporation, Eden Prairie, MN, USA

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Results

The power analysis performed using data from the first four pairs of limbs demonstrated that a significant difference could be obtained with 10 paired limbs. During the testing, the maximal displacement of the machine was achieved before the failure point was reached in one specimen. At this point, the maximum force recorded was 8611 N of axial load. Therefore, the data from this pair of limbs was removed from the statistical analysis. Evaluating data from the remaining nine limb pairs, we found that the mean load at failure of the LCP construct (4968 N ± 2167) was significantly greater than for the screw constructs (3009 N ± 1091) (p <0.01) (Figure 3). There was large inter-individual variation of the failure point between pairs of limbs (Figure 4). The screw technique was stronger than the LCP technique in just one pair of limbs. In all other pairs, the plate construct was stronger than the screw construct (Figure 5). No significant difference was found in the metacarpophalangeal joint angle of dorsiflexion between the limbs of the same pair neither before nor after testing, demonstrating that limb position was consistent between limbs.

The most common failure mode in limbs repaired with the LCP construct (n = 9) was a comminuted fracture of the apical fragment of the proximal sesamoid bone. A fracture in the distal fragment of the sesamoid bone occurred in one limb. The locking screw was avulsed from the Combi-hole® of the LCP in one limb. One specimen did not break during the test, but a gap between the two fragments, and screw bending in a proximal direction were evident on examination after testing. A concomitant fracture of the lateral proximal sesamoid bone was observed in six of the 10 limbs.

In limbs repaired with the screw technique, a comminuted fracture of the apical fragment of the proximal sesamoid bone was evident in all limbs except one specimen (9/10) that broke the distal fragment of the proximal sesamoid bone. The screws were bent in all limbs, and a concomitant fracture of the lateral proximal sesamoid bone was observed in five out of 10 limbs. No suspensory ligament or distal sesamoidean ligament disruptions were observed in any limbs.

Discussion

The results of our in vitro cadaveric limb study indicate that loads to failure of transversely osteotomized proximal sesamoid bones was greater for repairs with a two-hole 3.5 LCP hybrid construct than repairs with a single 4.5 mm cortical screw in lag fashion. The large inter-subject variation observed in our study was consistent with the findings in previous biomechanical testing studies (9, 10, 13).

A learning curve was present during limb preparation, particularly with regards to the placement of the LCP. During specimen preparation, we found that the sesamoid bone was very hard and difficult to drill with a 2.5 or 2.8 mm drill bit unless new sharp drill bits were used after which
there were no problems encountered in the application of the LCP. During the placement of the plate, the distal cortical screw was placed in a neutral position without problems in all limbs. However, the proximal locking head screw could not be placed with the plate in contact with the bone due to the plate configuration; if the plate was bent the locking screw would cross the osteotomy line. Additionally, the shape of the sesamoid bone precluded satisfactory contouring of the two-hole plate. A gap between the bone and the plate was unavoidable in all specimens and could be a weak point of the construct (17). It is possible that a variation in the results occurs due to a learning curve and practical improvement over time, considering that the adequate placement of the plate and the correct positioning of the screws in the proximal fragment require technical expertise.

The configuration of the plate dictated that at least one cortical screw be placed in order to span the fracture line. The Combi-hole® design meant that the two locking screws holes were close together in the centre of the plate. It was elected to place the cortical screw distally where the plate was in contact with the bone, and a locking head screw proximally where the plate was distant to the bone to try to optimize the strength of the construct. However this resulted in the application of the LCP as a hybrid plate construct because of the mixture of locking and non-locking screws. Changing the plate hole design to allow two locking head screws is a potential point to improve the plate performance in the future.

Considering that the limbs used in this study were collected from abattoir horses with no information about age, breed or gender, or athletic use, the individual variation in itself can explain the inter-individual variation in the results. For example, untrained horses are more likely to show disruption of the suspensory apparatus through the soft tissues than through the proximal sesamoid bone, and also bone density and porosity changes with age and workload are well known (5, 18, 19). This could not be controlled or avoided in this study. For this reason, the comparisons were only done between paired limbs from the same horse. It has been reported that there were no significant morphological differences between right and left proximal sesamoid bones (20).

A comminuted fracture of the apical fragment was most commonly found as the cause of failure as previously described (9, 10). This apical fracture has been associated with the larger holding strength at the base of the bone by the screw head, but we did find the same failure point using a LCP (10). Concomitant fracture of the lateral proximal sesamoid bone was another common finding being present in 11/20 limbs. In previous studies, it was suggested that these findings were due to the fact that during bone osteotomy, the lateral sesamoid bone or the inter-sesamoidean ligament could be touched by the oscillating saw (9, 10). This hypothesis cannot be ruled out in our study, although this was not observed macroscopically. If this happens, a weak point could be created resulting in fracture. The lateral sesamoid was left intact in this study to mimic the clinical situation and as done in other studies on different fixation methods (9, 10).

Under axial load conditions, the third metacarpal or metatarsal bone applies a compressive force in the articular surface of the proximal sesamoid bone at the same time that the suspensory apparatus applies a tensile force in the palmar or plantar surface of the bone (21). During exercise, these forces are applied in a cyclic way and the bone and the constructs undergo a cyc-

**Figure 3** Comparison of the mean load to failure between the limbs with an osteotomized proximal sesamoid bone repaired with a locking compression plate and those repaired with a cortical screw. The repair with the plate technique was significantly stronger than the screw technique with p <0.01.

**Figure 4** The graph shows the force at the failure point for each paired limb where the light gray bars represent the limb repaired with a 3.5 mm locking compression plate and the dark gray bars represent the limb repaired with a 4.5 mm cortical screw.
lic fatigue that can result in a fracture or implant failure (19). Considering that just a single cycle test was performed in this study, it is not possible to relate our results to a clinical situation. A cyclic test needs to be performed in the future to test whether the plates are stronger than screws in a fatigue situation before considering a clinical application. This study was a pilot study to determine if further study was worth performing. Additionally the exact loads on the sesamoid bone were not measured in this experiment, which would be an interesting addition to future studies. The plate was positioned just palmar to the dorsal branch of the suspensory ligament to reduce the damage to this ligament, considering that the prognosis of the surgical correction for proximal sesamoid bone fractures is closely related to the degree of suspensory desmitis (15, 22, 23). Nevertheless, the proximal screw was placed through some suspensory attachments to the sesamoid bone and the plate lies over the collateral sesamoidean ligament. The clinical significance of this soft tissue impingement under cyclic load should be studied before clinical application.

Racehorses with well-reduced proximal sesamoid bone fractures have a better outcome after surgery because of reduced motion of the fragments and a faster healing of a bone with known deficit in the blood supply (7, 19). The LCP could be a good option to retain the reduction, reduce interfragmentary micromotion and be a stronger construct for proximal sesamoid bone fractures. However, a modified plate design would be needed to improve the contact with the bone and facilitate the screw application. It might be useful to have locking head screws on both sides of the fracture and potentially two holes in the basilar fragment to allow a better fixation of the bone. The replacement of the Combi-hole® design for a single round locking hole design could facilitate the application and increase the fatigue resistance of the plate.

This study compared plate fixation with a single cortical screw fixation as the latter has been the published technique with the most success and has been studied in other biomechanical testing studies (7, 9–13). While in the clinical situation, some surgeons may use two screws placed in lag fashion, this technique has not been published or submitted to biomechanical testing to our knowledge. An interesting future study could compare two screws, one screw, and the plate in cyclic fatigue testing.

In conclusion we found that the 3.5 LCP applied as a hybrid plate was significantly stronger than one 4.5 cortical screw for correction of mid-body proximal sesamoid bone osteotomies when tested in an in vitro biomechanical single cycle to failure study and could be a potential treatment option for mid-body proximal sesamoid bone fractures of this bone after further study.

Acknowledgements

The limbs used in this study were prepared in the Centre Hopitalier Universitaire Vétérinaire at the Université de Montréal and they were tested in the Laboratoire de recherche en imagerie et orthopédie at the Hôpital Sacré Coeur de Montréal.

Conflict of interest

The authors do not declare any interest or financial conflicts. The study was partially funded by the Fond de Recherche Clinique de Pfizer Santé Animal.

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