1-1-2013

Arthrodesis of the Proximal Interphalangeal Joint in the Horse: A Biomechanical Comparison of 5.5mm Cortical Screw Augmented 4.5mm Narrow LCDCP And 5.0mm LCP Constructs With and Without Distal Interphalangeal Joint Collateral Ligament Transection

Richard A. Rocconi

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By

Richard A. Rocconi

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Veterinary Medical Sciences
in the College of Veterinary Medicine

Mississippi State, Mississippi

August 2013

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By

Richard A. Rocconi

Approved:

Ron M. McLaughlin, Jr.
Professor
Clinical Sciences
(Major Professor)

Robert L. Linford
Professor
Clinical Sciences
(Committee Member)

Steven H. Elder
Professor
Agricultural and Biological Engineering
(Committee Member)

Andrew J. Mackin
Professor
Clinical Sciences
(Graduate Coordinator)

Mark L. Lawrence
Associate Dean
College of Veterinary Medicine

Name: Richard A. Rocconi

Date of Degree: August 17, 2013

Institution: Mississippi State University

Major Field: Veterinary Medical Sciences

Major Professor: Ron M. McLaughlin, Jr.

Title of Study: Arthrodesis of the proximal interphalangeal joint in the horse: A biomechanical comparison of 5.5mm cortical screw augmented 4.5mm narrow LCDCP and 5.0mm LCP constructs with and without distal interphalangeal joint collateral ligament transection

Pages in Study: 19

Candidate for Degree of Master of Science

The *in vitro* comparison of monotonic and cyclic mechanical properties of equine proximal interphalangeal joint arthrodeses stabilized using an open or closed technique and application of 2 abaxial transarticular lag screws combined with either an axial 4.5mm narrow 3-hole LC-DCP with 5.5mm cortical screws a 4.5mm narrow 3-hole LCP with 5.0mm locking screws. Limbs were tested for cyclic fatigue at 20,0000cycles and then in single-cycle to failure under 3-point, dorsopalmar bending. There were no significant differences in stiffness and single-cycle to failure values between the LCP and LC-DCP constructs, with or without PIPJ collateral ligament transaction. There was no interaction between the open and closed techniques, nor between plate types on force or stiffness at failure.

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CHAPTER I

INTRODUCTION

Osteoarthritis is common condition in horses and is a frequent cause of lameness in the performance horse. Arthritic conditions of the proximal interphalangeal joint (PIPJ) are often diagnosed in horses that are used for disciplines that require high energy stops or turns.[1]The disease process is invariably progressive and long-term medical management is often unsuccessful.[2]Chronic osteoarthritis of the PIPJ is often debilitating and can cause a drastic reduction in the quality of life in advanced cases.[1]The PIPJ is classified as a high load-low motion joint which makes it amenable for arthrodesis while maintaining the potential for athletic performance.[1-3] PIPJ arthrodesis is indicated for a variety of disorders affecting the PIPJ such as: osteoarthritis, septic arthritis, unstable joint injuries, articular fractures, and developmental orthopedic disease.[1-6]

Several techniques for performing PIPJ arthrodesis have been described. [1-20]The currently preferred technique includes the application of a single, axially positioned dorsal plate with two transarticular (TA) screws placed in lag fashion.[1,2, 5, 13, 21]The use of several different plate types has been reported, including the Locking Compression Plate (LCP), Dynamic Comperssion Plate (DCP) and Limited-Contact Dynamic Compression Plate (LC-DCP). The Locking Compression Plate (LCP) has been reported to be the preferred implant for osteosynthesis of equine long bones because it exhibits increased stiffness under high-load applications compared with other available implants.[32] Stronger constructs decrease the need for external coaptation, allowing earlier cast removal, decreased incidence of cast sores, and shorter hospitilization.[5] Previous studies failed to demonstrate a significant clinical advantage of using an LCP over the use of a DCP construct for PIPJ arthrodesis in the horse.[18,19] However, results of a recent report comparing LCP and LC-DCP constructs tested in 4-point bending found that LCP constructs had a higher stiffness and similar strength.[30]

Less invasive arthrodesis techniques avoid the need to disarticulate the joint to remove the articular cartilage and allow preservation of the collateral ligaments.[12,15,16,22-29] Intact collateral ligaments are theorized to strengthen the arthrodesis construct by continuing to aid in joint stability. Additionally, less invasive techniques potentially decrease postoperative pain, reduce the incidence of postoperative infection and wound dehiscence, and may decrease surgical time and expense.[12,29]

Cartilage removal by drilling is one technique in horses that has been proven to achieve arthrodesis in the tarsometatarsal, distal intertarsal, and carpometacarpal joint.[2,22-24,26] A dorsal drilling approach to the PIPJ has reported to provide satisfactory results in a study in which optimal drill bit size was determined to be 4.5mm.[16]

The purpose of this in vitro study was two-fold: (1) to compare the monotonic and cyclic biomechanical properties of an axial LCP in conjunction with two abaxial transarticular cortical screws inserted in lag fashion (LCP-TLS) with a similarly positioned LC-DCP (LC-DCP-TLS); (2) to compare an open technique with collateral ligament transection and conventional cartilage removal to a closed technique with minimally invasive cartilage removal for PIPJ arthrodesis.

The hypothesis was that there would be no significant difference in stiffness or failure load between constructs or techniques.

CHAPTER II

MATERIALS AND METHODS

Study Design

Forelimb pairs (n=10) intact from the mid-cannon bone distally were collected from adult horses euthanized for reasons unrelated to orthopedic disease. Mean ±SD age of the horses studied was 7.2 ± 4.59 years (range, 3-17 years). There were 6 geldings and 4 mares, with 5 Quarter Horses, 2 Thoroughbreds, 2 Paints, and 1 Tennessee Walking Horse. All limbs were stored in pairs at -20°C. Before preparation for testing, limb pairs were thawed at room temperature (20-22°C) for 12 hours. Forelimbs were randomly divided into 2 construct groups: (5 pairs LCP-TLS) and (5pairs LC-DCP-TLS). Right and left forelimbs were randomly selected for the open (O) technique or the closed (C) technique. All limbs were tested in 3-point bending cyclic fatigue to a total of 20,000 cycles[18] and then in 3-point bending single cycle to failure[8-10,14,16,17].

Open Joint Approach/TLS Placement

A standard approach to the PIPJ was used.[2,4] The collateral ligaments were transected, the PIPJ was disarticulated, and the articular cartilage from the distal articular surface of the proximal phalanx and the proximal articular surface of the middle phalanx was completely removed using a bone curette.

For placement of the transarticular lag screws, a combined aiming device (Synthes Vet Ltd.) was used for consistent glide hole drilling in the proximal phalanx. The location of the two holes for the transarticular screws were marked by the pointed hook of the combine aiming device midway between the dorsal and palmar cortices and in a slightly diverging direction. Two 5.5mm glide holes were drilled in a proximal to distal direction. A 4.0mm drill sleeve was inserted into the first glide hole and a4.0mm thread hole was drilled in the middle phalanx. A countersink was used to prepare depressions in the bone for the head of the transarticular screw. The thread hole was tapped, and a 60mm/5.5mm cortical screw was inserted but not tightened tightened. The same was repeated for the other transarticular screw. After the placement of both screws, each was tightened.

Closed Joint Approach/TLS Placement

A standard approach to the PIPJ was used as above, however, the PIPJ collateral ligaments were not transected and a 4.5mm drill bit was used for cartilage removal. Under fluoroscopic guidance, an 18g x 1.5" needle was used to mark the locations for 4 different drill entry tracts through the joint. For Tract 1, a stab incision was made through the subcutaneous tissue and joint capsule just palmar to the lateral collateral ligament. A drill guide was used to center a 4.5mm drill bit within the stab incision and an intra-articular drill tract was made in a lateral to medial direction to exit the joint just palmar to the medial collateral ligament. Tract 2 was made parallel to tract 1, but dorsal to the lateral collateral ligament using the same technique. Tract 3 was started just lateral to the common digital extensor tendon (CDET) and directed at a 60° angle towards the center of the medial palmar eminence, and then redirected (tract 4) palmarly towards the ipsilateral palmar eminence. Tract 5 was started just medial to the CDET, and directed at a 60° angle towards the center of the lateral palmar eminence, and then redirected (tract 6) palmarly towards the ipsilateral palmar eminence. The drill bit was forced to advance in a parallel manner through the joint for drill tracts 1 & 2. For drill tracts 3,4,5, & 6, the drill bit was allowed to follow the contour of the joint surface. In all tracts, advancement was stopped before disruption of the periarticular soft tissue structures on the opposite side of the joint occurred.

The transarticular lag placement was performed under fluoroscopic guidance. Care was taken to ensure that each 5.5mm glide hole completely entered the joint but did not extend into the second phalanx. The completion of the TLS procedure was identical to that of lag screw placement utilizing the open technique.

LCP Technique

A 3-hole, 4.5mm LC-DCP, without contouring, was placed dorsal and axial over the PIPJ. The plate was positioned so that the distal screw hole was at the proximal extent of the second phalanx. A 4.3mm threaded drill guide (Synthes Vet Ltd.) was inserted into the distal most hole, a 4.3mm hole was drilled through both cortices of the middle phalanx, and a 70mm/5.0mm locking screw was inserted, but not tightened. Using the drill guide in the middle screw hole, a 4.3mm hole was drilled through both cortices of the proximal phalanx, and a 70mm/5.0mm screw inserted exactly as in the distal hole. The same steps were completed for the most proximal screw hole. A torque screwdriver (CDI Torque Products, City of Industry, CA) was used to tighten the locking screws to a torque of 4.0Nm. A standard closure of the CDET and skin was performed.[29]

LC-DCP Technique

A 3-hole, 4.5mm LC-DCP, without contouring, was placed dorsal and axial over the PIPJ, with the distal hole placed over the proximodorsal aspect of the middle phalanx. Using an LC-DCP drill guide (Synthes Vet Ltd.) in neutral position, a 4.0mm hole was drilled perpendicular to the plate, through both cortices of the middle phalanx in the distal most LC-DCP hole. The hole was tapped and a 45mm/5.5mm cortical screw was inserted but not completely tightened. The LC-DCP was pulled proximally and a second hole was drilled through both cortices of the proximal phalanx perpendicular to the plate, using a LC-DCP drill guide in load position in the middle LC-DCP hole. The hole was tapped and a 45mm/5.5mm cortical screw was inserted but not completely tightened. A third hole was drilled through both cortices of the proximal phalanx parallel to the central screw using an LC-DCP drill guide in neutral position in the proximal LC-DCP hole. The hole was tapped and a 45mm/5.5mm cortical screw was inserted but not completely tightened. All screws were subsequently tightened in an alternating manner to a final insertion torque of 4.5Nm. A standard closure was performed as described for the LCP-TLS technique.

After completion of each construct, lateral and dorsopalmar fluoroscopic images were obtained to ensure proper implant placement.

Mechanical Testing

All limbs were tested in dorsopalmar three-point bending using a MTS Bionix 858 Testing System frame equipped with 5 kN load cell (MTS Systems Corporation, Eden Prairie, MN) and interfaced with a Test Resources 235-2S-L Series Controller (Test Resources, Inc., Shakopee, MN) and MTL Windows Control software (MTL7_1.001).

Each limb was secured in a custom fixture specifically designed for the purposes of this study. In the hoof of each limb, a 14.3mm hole was drilled at a 90^0 angle from the apex of the frog through the dorsal aspect of the hoof wall approximately 1.0 cm distal to the coronary band. A 12.7mm bolt was inserted in this hole from the solar aspect to firmly attach the hoof to the customized limb fixture.

Each limb was subjected to 20,000 cycles of 6 Hz sinusoidal loading under compressive force control to upper and lower limits of 3500 N and 500 N, respectively. Load and displacement were captured at approximately 330 Hz. After completion of the cyclic phase of loading, limbs were loaded to failure under stroke control at a constant rate of 19.0mm/s. Load and displacement were recorded at 100 Hz.

Data Analysis

For cyclic loading the dynamic stiffness was calculated as the peak-to-peak force divided by the peak-to-peak displacement for a given cycle. Initial dynamic stiffness was averaged over 5 consecutive cycles starting at the 301^{st} cycle, which is approximately when the desired load limits were first achieved. The final dynamic stiffness was averaged over the last 5 consecutive cycles of the 20,000 cycle test.

Load versus displacement curves were constructed for each monotonic test to failure. Stiffness was calculated as the slope of the best fit line through the initial linear region of the curve. Failure load (and associated displacement) was determined as the local maximum preceding the first sudden decline in force.

Statistical Analysis

Data were examined for normality of distribution, descriptive statistics were applied and data were then categorized into monotonic (single cycle to failure) and cyclic failure groups. Normally distributed data were examined using a Student's two-sample T-test. The potential interaction between open and closed techniques with construct choice was examined using a factorial analysis of variance. Overall cyclic fatigue test results (initial and final stiffness) were examined using a paired T-test. Significance was set at $p< 0.05$.

CHAPTER III

RESULTS

Cyclic Loading

While initial construct stiffness was normally distributed with a mean stiffness of 951.94Nmm (+/- 97.48, range 724.12 to 1129.3), final stiffness had a single outlier that was more than two standard deviations outside the normal range skewing data into non-normal distribution. As such this construct was removed from all further data analysis (final n=19). Final construct stiffness was therefore 920.1Nmm (+/- 103.7, range 768.4 to 1103.1). There was a trend for final stiffness to be less than initial stiffness (36.82Nmm) but this difference was not significant (p=0.09).

Open constructs (n=9) had an initial mean stiffness of 981.4Nmm (+/-88.03, range 860.72 to 1129.3) and a final mean stiffness of 931.1Nmm (+/- 91.34, range 813.4 to 1103.1). Closed constructs (n=10) had an initial mean stiffness of 934.9Nmm (+/- 104.81, range 724.12 to 1065.4) and a final mean stiffness of 909.3Nmm (+/- 117.56, range 768.4 to 1082.8). There was no significant difference in any of the variables (initial, final and difference between initial and final stiffness) between open and closed constructs (p=0.31, 0.62 and 0.52 respectively).

Constructs completed using the LC-DCP (n=9) had an initial mean stiffness of 940.42Nmm (+/-118.01, range 724.12 to 1129.3) and a final mean stiffness of 895.46Nmm (+/- 109.49, range 772.2 to 1103.1). Those completed using the LCP (n=10) had an initial mean stiffness of 971.77Nmm (+/-78.2, range 830.8 to 1065.4) and a final mean stiffness of 942.28Nmm (+/- 98.45, range 768.4 to 1082.8).

There was no significant difference between initial and final stiffness between LCDCP and LCP constructs (p=0.50, 0.34). LCP constructs tended to have a lower difference between initial and final stiffness (-29.5Nmm) compared to LCDCP constructs (-44.96Nmm), however this was not mathematically significant (p=0.72). There was no significant interaction between open technique (yes or no) and plate type (LCDCP or LCP) on any of the variable outcomes tested (p=>0.59).

Monotonic Failure

This data was normally distributed and all 20 constructs were included. Overall mean force at failure was 20296N (+/-SD 2231.2N, range 15545 to 23564N). Mean stiffness at failure was 1181.6Nmm (+/- 335.44, range 744.54 to 2037.3).

Open constructs (n=10) had a mean force at failure of 20307N (+/- 1797.2, range 17714 to 22705) and a mean stiffness of 1316.3Nmm (+/- 405.27, range 785.01 to 2037.3). Closed constructs (n=10) had a mean force at failure of 20284N (+/- 2698.1, range 15545 to 23564) and a mean stiffness of 1046.8Nmm (+/- 181.53, range 744.54 to 1286.4). Closed constructs failed with a greater mean force (23.0 N, p=0.98) and there was a non-significant trend for them to be stiffer (269.50Nmm, p=0.07) than open constructs. A post-hoc power calculation using a 95% confidence interval and 80% power indicates that 21 constructs per group would have had to have been used to be confident that this result was truly not significant.

Constructs completed using the LC-DCP (n=10) had a mean force at failure of 20460N (+/- 2212.5, range 17006 to 23564) and a mean stiffness at failure of

1187.1Nmm (+/- 332.11, range 785.01 to 1928.7). Those completed using the LCP (n=10) had a mean force at failure of 20132N(+/- 2356.9, range 15545 to 23171) and a mean stiffness at failure of 1176.1Nmm (+/- 356.63, range 744.54 to 2037.3). The LC-DCP had a greater force (328.40N) and stiffness at failure (11.004Nmm) than the LCP constructs (p=0.75 and 0.94 respectively).

There was no significant interaction between open technique (yes or no) and plate type (LC-DCP or LCP) on either force (p=0.81) or stiffness at failure (p=0.87).

CHAPTER IV

DISCUSSION

There were no significant difference between the LCP and LC-DCP constructs with or without PIPJ collateral ligament transection when the biomechanical properties of stiffness and single cycle to failure after 20,000 cycles under 3-point dorsopalmar bending were assessed. There was no significant interaction between cartilage removal technique and plate type on either force or stiffness at failure.

The optimal model for testing the biomechanical properties of PIPJ arthrodesis constructs has not been determined. PIPJ arthrodesis constructs are often tested in axial compression[11,13,19,20], 3-point, and 4-point bending[8-10,14,16-18,30]. Axial compression testing attempts to mimic the *in vivo* weight bearing and cyclic forces acting on the equine distal limb. However, three and four point bending offer other ways to assess the biomechanical properties of constructs and may limit testing variation. Using these testing models, force is focused more closely on the construct and may be a more accurate way to test the strength on an implant or implant combination. The comparison of results from other testing models (axial compression or 4-point bending to 3-point bending) is difficult given the different force vectors and their orientation to the construct. One must also consider the presence or absence of palmar soft-tissue structures and how they interact with implant constructs to stabilize the dynamic forces acting on the equine distal limb.

There was no significant difference between the LCP-TLS and (LC-DCP)-TLS constructs in the testing model used in this report. Three published reports have compared similar construct combinations.[18,19,30] Sod et al found the DCP-TLS combination to provide greater stability under axial compression in single cycle to failure than the equine pastern arthrodesis plate (ELCP)-TLS construct. The ELCP-TLS construct provided significantly greater stability under torsional loading in single cycle to failure. No significant difference in stability was found between the 2 constructs for cyclic loading under axial compression.[19]Zoppa et al found no significant difference between a LCP-TLS construct and a 3-hole DCP-TLS construct when tested under cyclic testing and single cycle to failure under axial compression.[18]Ahern et al found a significant difference in stiffness when comparing an ELCP-TLS construct to an (LC-DCP)-TLS construct. However, overall strength was comparable.[30]

Comparisons between these reports and ours is difficult because of differences in plates as well as models used for testing. This study used the a 3-hole 4.5 mm narrow LCP (Synthes Vet Ltd, Paoli, PA) instead of the 3-hole 4.5 mm narrow ELCP plate. At the time of procurement of the implants, the 3-hole standard LCP was still in production and the new ELCP was not yet available. The 4.5mm 3-hole ELCP is similar to the 4.5mm narrow 3-hole LCP used in this study with the exception of having only one tapered end, being 4 mm longer, and having one stacked combi hole at the non-tapered end with 25 mm of elongation between the distal and middle regular combi hole. The LC-DCP plate is 3mm shorter than the DCP and has 18mm of spacing between each hole. The DCP has 25mm between the distal and middle hole and 16mm between the middle and proximal holes. Although similar, the differences in these plates makes direct comparison with the before mentioned reports impossible.

Given our findings and that of other authors evaluating similar construct combinations, there may be little evidence to justify the use of the LCP or ELCP over LC-DCP or DCP constructs for pastern arthrodesis in the horse. In addition to requiring expensive special instrumentation for their application, the expense of the two construct combinations is significantly different and may cause locking plates to be cost prohibitive in some cases. The 3-hole 4.5 mm narrow ELCP costs approximately 300% of the price of the 3-hole 4.5 mm narrow LC-DCP. Intact soft-tissue structures on the palmar/plantar aspects of the pastern are thought to lend great strength to the region and are loaded in tension in dorso-palmar/plantar 3-point bending. These structures are left intact when performing pastern arthrodesis *in vivo*. However, the collateral ligaments of the pastern joint are severed to allow the joint to be disarticulated to aid in cartilage removal for most methods. Methods for removing articular cartilage using laser or drilling without transecting the collateral ligaments have been reported (Bras et al, Watts et al).[15,16] (Bras et al) used a 4.5 mm drill bit to drill seven evenly spaced parallel tracks through the joint space over distal P1 in a dorsal to palmar direction. We chose a slightly different drilling technique in an effort to remove a greater proportion of articular cartilage from all areas of the joint surface. This amount of cartilage removed was not quantified as it was not the focus of the paper. However, with having only four entry points of the drill bit, the technique was fast and easy to perform.

Collateral ligament sparing technique afforded no statistically significant increase in stiffness or force at failure when coupled to each implant combination when tested in dorso-palmar three-point bending. Admittedly, collateral ligaments stabilize the medial and lateral aspect of joints and lend most of their strength to shear, bending and torsional forces. In this testing model, intact collateral ligaments might be expected to provide little strength in the physiologic range of motion for the pastern joint. However, to our knowledge, the amount of strength afforded by the collateral ligaments outside of that physiologic range of motion has not been studied. Since the arthrodesis constructs were placed with the limbs in full extension, the possibility existed that intact collateral ligaments might have added some strength in 3-point dorso-palmar bending which over extends the joint. Intact collateral ligaments may play an important role further along in the ankylosing process. Our cyclic testing ended at 20,000 which is far short of the number of cycles the average PIPJ experiences before functional arthrodesis is achieved. Further work is necessary to evaluate the strength of intact collateral ligaments and what role they play throughout the process.

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