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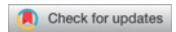
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An Investigation of a Novel Tendon Transfer Surgery for High Median-Ulnar Nerve Palsy in a Chicken Model

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ABSTRACT

Purpose: The state-of-the-art tendon transfer surgery for high median-ulnar nerve palsy involves directly suturing four finger flexor tendons to one wrist extensor muscle. This couples finger flexion limiting the patient's ability to grasp objects. Therefore, we propose a new approach to attach a novel passive implant to the extensor digitorum longus tendon in order to create a differential mechanism *in situ*. The implant is expected to enable the fingers to adapt to an object's shape during grasping. Chickens have been used as a model in tendon research, but studies have primarily focused on the digital flexor tendon mechanism. Thus, the aim of this study was to explore the feasibility of the chicken model for extensor tendon research and to validate the surgical technique for a new approach to tendon transfer surgery. *Materials and Methods*: Twenty-nine chickens were randomly divided into three groups: implant (n = 12), sham (n = 10), and control (n = 7). Postoperative healing and complications were documented. *Results*: Surgery was successful in all chickens. All animals healed appropriately by Day 16 postoperatively. Chickens in the implant group experienced significantly more intermittent toe-knuckling gait than the sham group (p = 0.001). *Conclusions*: The described surgical technique allowed for successful application of a novel implantable passive mechanism in a live chicken model. In combination with previous work, findings from the present study further validated a novel tendon-transfer surgery for high median-ulnar nerve palsy. Based on the degree of intermittent abnormal gait experienced by the implant group, refinement to the implant design is warranted in future studies.

Keywords: chicken; extensor tendon; implant; tendon transfer surgery; high median-ulnar nerve palsy

INTRODUCTION

High median-ulnar nerve palsy is a neuromuscular condition in which the median and ulnar nerves in the forearm are disabled or damaged. As a result, all four muscle bellies of the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), and the intrinsic hand muscles become incapacitated leading to complete loss of sensory, finger flexion, and other related deficits in hand function [1]. A common approach to restoring finger flexion for this condition is a tendon transfer surgery that involves detaching all four FDP tendons from the distal ends of their disabled muscle bellies and directly suturing them to the single-belly extensor carpi radialis longus (ECRL) muscle innervated by the unaffected radial nerve [2, 3, 4]. With this new biomechanical tendon routing, finger flexion is made possible when the ECRL contracts. Unfortunately, despite restoration of finger flexion, the sutures between the FDP tendons and the ECRL muscle couple the movement of all four fingers. This prevents the fingers from individually adapting to an object's shape during physical interaction tasks, such as grasping [5, 6]. Specifically, when one finger makes contact with an object, that finger becomes fixed due to the prescribed tendon coupling and inherently inhibits

the other fingers from closing in. In this situation, the patient will be forced to perform compensatory movements, such as rotating the wrist and/or forearm or using a much greater muscle force to stretch the tendon of the finger that has already made contact, for a successful multi-finger grasp. In summary, the current tendon-transfer surgery for high median-ulnar nerve palsy produces limited hand function for the patient in daily living activities [6].

To address the limitations of the state-of-the-art tendon transfer surgery for high median-ulnar nerve palsy, our group is developing a new surgical procedure that utilizes a novel passive implantable mechanism incorporated into the tendon network. Specifically, instead of just using sutures to attach the FDP tendons to the ECRL muscle, we seek to surgically create a "differential mechanism" *in situ* in the forearm using the biological tendons and an artificial implant. The implant will mechanically distribute the movement created by ECRL muscle contractions across the FDP tendons and enable the fingers to move adaptively even if driven by one muscle. The constructed differential mechanism within the forearm will enable the fingers to passively adapt during multi-finger grasping, wherein even after one finger makes contact, the other fingers can continue to move similar to how the differential mechanism in automobiles allows the outer drive wheel to spin faster and travel further than the inner drive wheel during a turn.

In order to validate this concept, the authors have created embodiments of the differential mechanism in previous work that were simpler but progressively more appropriate for surgical application. It was first shown in human cadavers that a differential mechanism in the form of off-the-shelf pulleys between the muscle and the tendons demonstrated significant improvement in adaptive grasping function compared to the current suture-based procedure. Second, OpenSim (NCSRR, Stanford, CA, USA) biomechanical simulations were used to show that a differential mechanism in the form of a moving lever (seesaw) mechanism also provided adaptive finger movement [7, 8]. Third, a differential mechanism in the form of a translating, pivoting triangle created using the biological tendons and a single piece strut continued the trend and further exhibited adaptive extension between the toes in the cadaveric chicken foot [9]. The chicken extensor digitorum longus tendon mechanism was the chosen model for this surgery because the tendon mechanism resembles the coupled human hand flexor mechanism after the suture-based tendon transfer surgery. Following these aforementioned validation studies and with the long-term goal of developing passive implantable mechanisms to improve the current human tendon transfer surgery, our group conducted an *in vivo* pilot study using the chicken model. The contribution of the present study is two-fold. First, we explore the feasibility of the chicken model for *in vivo* extensor tendon surgery research since studies in chicken models have primarily focused on *ex vivo* flexor tendon surgery research [10, 11]. Second, we describe the surgical technique required for tendon surgery involving the attachment of an implant in the extensor tendon network of a chicken model.

MATERIALS AND METHODS

Animals

Twenty-nine domestic Cornish Cross chickens (*Gallus gallus domesticus*) were used in the study under approval and oversight of the Institutional Animal Care and Use Committee (IACUC) of Oregon State University (Corvallis, OR, USA). Nineteen females and ten males were included. Males were individually housed and hens were group-housed preoperatively, followed by postoperative individual or paired housing. At the time of study, animals were approximately 5.5 months of age. The average body weight of the chickens was 4.9 kilograms.

Experimental Design

The implant was made of ultra-high-molecular-weight polyethylene, manufactured through computer numerical controlled (CNC) machining, and autoclaved for sterilization prior to implantation (Figure 1). The implant measured approximately 10 millimeters long, 4 millimeters wide, and 1 millimeter thick. Chickens were randomly assigned to one of three groups: implant (n = 12), sham (n = 10), and control (n = 7). The implant group underwent surgery and had an implant (Figure 3 and 4) sutured to the extensor digitorum longus (EDL) tendons. The sham group underwent surgery and only had the EDL tendons sutured at the same location relative to the bifurcation as if an implant was inserted (Figure 6). Chickens in the control group underwent no surgical intervention.

Preoperative Preparation and Anesthesia

Animals in the sham and implant groups were fasted overnight prior to anesthesia. Each chicken was premedicated with butorphanol (1 mg/kg) intramuscularly in the pectoral muscle and placed in a quiet, dark holding area for ten minutes. Level of sedation ranged from none to mild. Each animal was induced in sternal recumbency with isoflurane (2%) via facemask until working anesthetic depth was achieved. The animal was intubated with a 4.0-5.0 mm Cole endotracheal tube. Animals were maintained on isoflurane
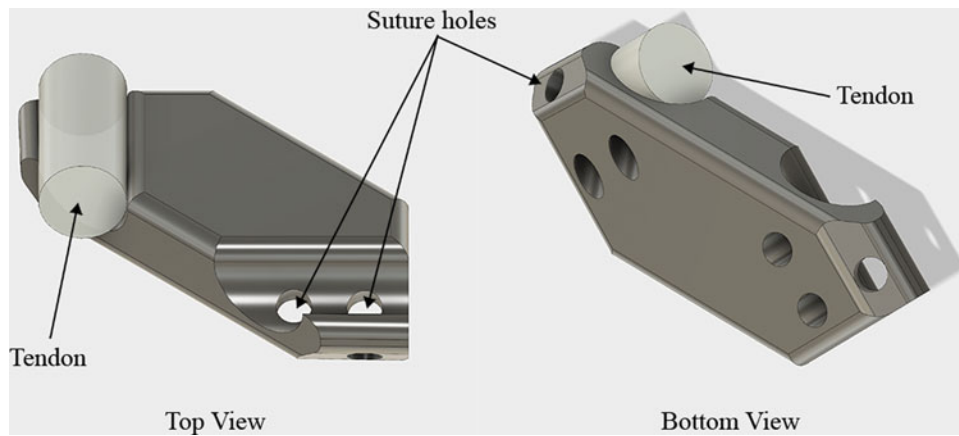
FIGURE 1   3-dimensional rendition of the implant illustrating the three suture holes and where biological tendons were positioned in the grooves.

(1.2-2.5%). Temperature, respiratory rate, heart rate, end tidal carbon dioxide, pulse oximetry, and electrocardiography were monitored throughout the procedure. Enrofloxacin (6 mg/kg) was administered intramuscularly in the pectoral musculature following induction. Butorphanol (1 mg/kg) was given intramuscularly at the end of each surgical procedure. Animals were placed in sternal recumbency after discontinuing isoflurane for recovery and extubated once they had regained laryngeal function and control of their head. Each animal was given access to feed and water once they could stand.
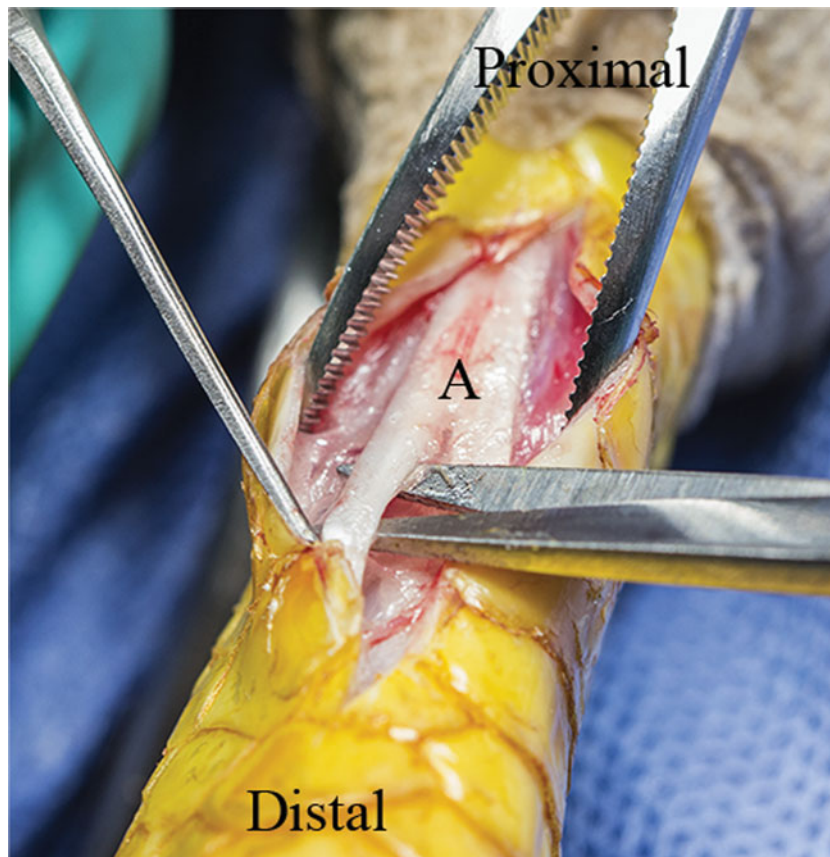

FIGURE 2   After the scales were incised, the EDL tendons were dissected from the deep surrounding tissue just distal of the bifurcation (A) using sharp-sharp scissors. Mosquito hemostats were used to achieve retraction and maintain exposure during the procedure.
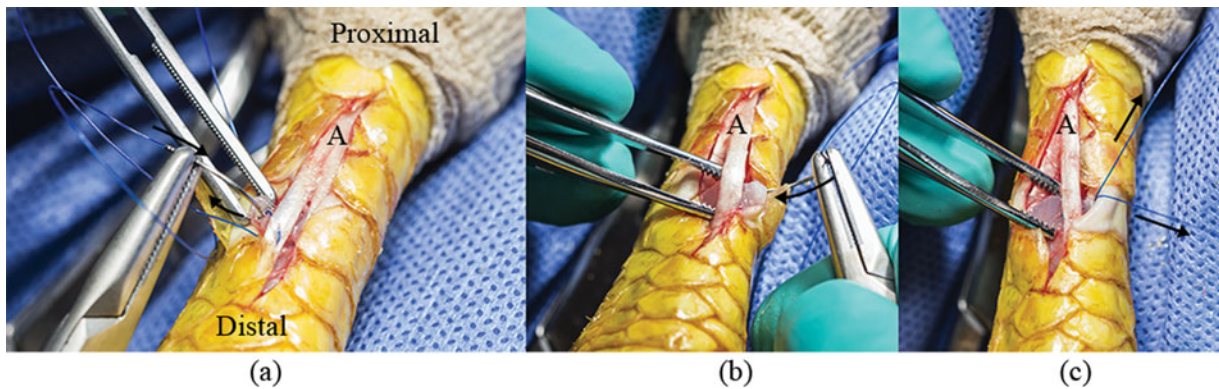
FIGURE 3   Implant-based surgery. Following the incision and dissection from the surrounding tissue, the implant was placed deep to the EDL tendon just distal of the bifurcation (A) using Debakey tissue forceps (a). The medial branch of the EDL tendon was sutured using 5-0 Prolene. Then, the lateral branch of the EDL tendon was sutured using 5-0 Prolene (b and c). For both sides of the implant, the tapered needle was guided through one suture hole, puncturing the deep surface of the tendon. Then the needle was guided back around, puncturing the superficial surface of the tendon, and pushed through the second suture hole. The square knots were made on the deep side of the implant.

Surgical Procedure

Surgery was performed by a board-certified veterinary surgeon on the left hindlimb of each animal. Hanging leg preparation was used along with aseptic technique. Three quarter drapes were placed around the leg, followed by a full drape. A tourniquet using sterile vet wrap was placed just proximal to the surgical site. Using a #10 scalpel blade a three-centimeter longitudinal incision was made on the dorsal surface of the tarsometatarsus. The skin was incised between the larger dorsal scales and the smaller secondary scales medially, and the medial spur was used as a midline landmark. Dissection using sharp-sharp scissors was performed to expose the EDL tendons beneath the fascia (Figure 2). The tendons were handled with Bishop Harmon tissue forceps, and implant was handled with Debakey tissue forceps. Exposure was maintained using mosquito hemostats (Figure 2). For the implant group, the implants were placed deep to the tendons approximately 5–8 millimeters distal to the EDL tendon bifurcation (Figure 3a). The implant was sutured with 5-0 polypropylene suture on a taper needle (Prolene) in each tendon longitudinally angled slightly off midline (Figure 3b). Square knots for each EDL tendon branch were oriented on the deep surface (Figure 3c). The resulting position and orientation of the implant prior to skin closure can be seen in Figure 4 and 5. For the sham group, the implant was positioned and then removed. Two single interrupted sutures were placed at the same location (Figure 6). The skin was closed in a cruciate pattern with 4-0 nylon suture on a reverse cutting needle (Ethicon). The skin was cleaned with iodine solution. Triple antibiotic ointment (bacitracin-neomycin-polymyxin B) was applied topically to the incision site. Finally, a bandage was placed over the incision using a telfa pad, cast padding, and vet wrap.
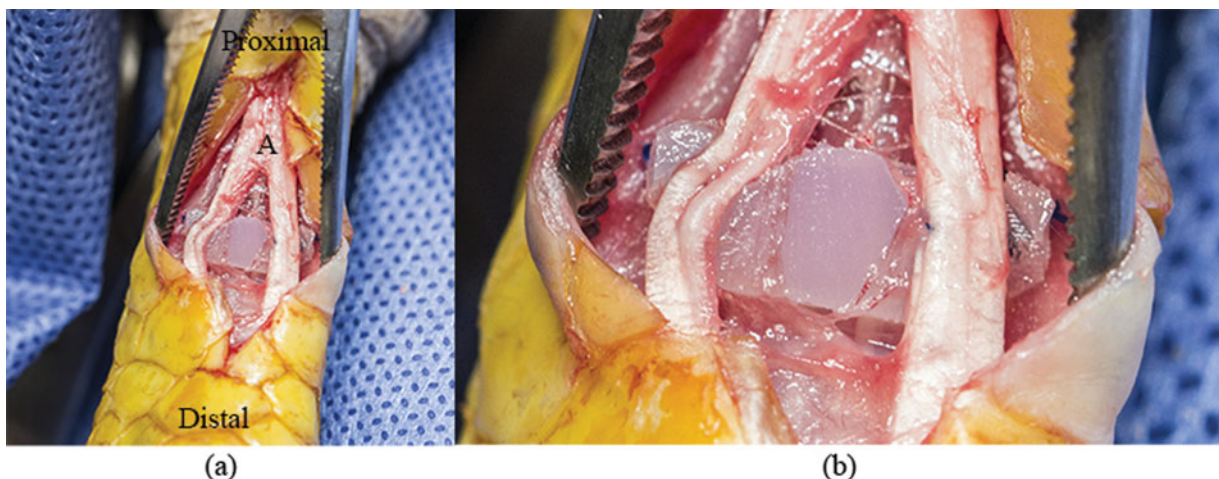

FIGURE 4   Once the two EDL tendon branches were sutured to the implant distal of the bifurcation (A), each branch sat appropriately in their respective grooves.
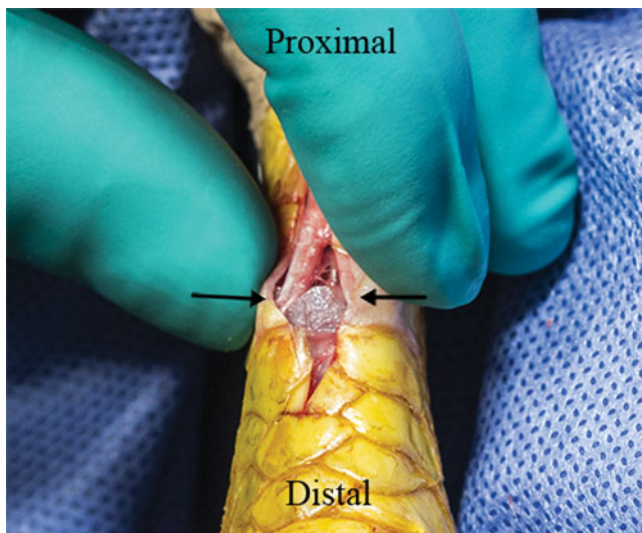
FIGURE 5   Skin was apposed over the implant prior to closure in a simple cruciate pattern. Varying degrees of skin tension around the implant were observed, but apposition of skin was achieved in all cases.

Postoperative Care

Animals were given an additional dose of butorphanol (1 mg/kg) intramuscularly in the evening following surgery. Wound healing was monitored daily for the first 10 days, followed by roughly every other day until bandaging was not needed. Bandages were initially changed daily followed by every other day until no drainage was observed. Triple antibiotic (bacitracin-neomycin-polymyxin B) ointment was applied topically to the incision site at each bandage change. Additional pain control, wound cleaning, and antibiotic therapy were provided as necessary. Incisions were assessed at each bandage change for discharge, swelling, bruising, scale loss, and progression of healing. The number of keratinized

scales lost as a result of surgical tissue handling was recorded for each chicken during initial bandage changes. The presence and quality of discharge (i.e. serosanguineous, caseous, etc.) was recorded throughout the follow-up period. Each animal was encouraged to walk daily for approximately 2–5 minutes, and their gait was assessed during this time. Food was used to entice each animal to walk in order to evaluate gait. Lameness was evaluated and scored according to a standardized gait scale from 0–5 validated by the USDA for scoring lameness in bubble feet pododermatitis [12, 13].

Statistical Analysis

Statistical analyses were performed using MedCalc for Windows (MedCalc Software, Ostend, Belgium) to evaluate differences between the implant and sham groups in terms of incisional drainage, the presence of knuckling, and scale loss. Data were tested for normality using the Shapiro-Wilk [14] and Shapiro-Francia tests [15]. Independent variable two-tailed t-tests were used at the $p = 0.05$ significance level.

RESULTS

Surgical Outcome

Surgical placement of the implant in the treatment group and sutures in the sham group was successful in all twelve and ten chickens, respectively. All animals recovered from surgery. There were no catastrophic complications that required major intervention or resulted in unacceptable function. Animals were unaffected by daily bandage changes and handling for lameness evaluation. The control group
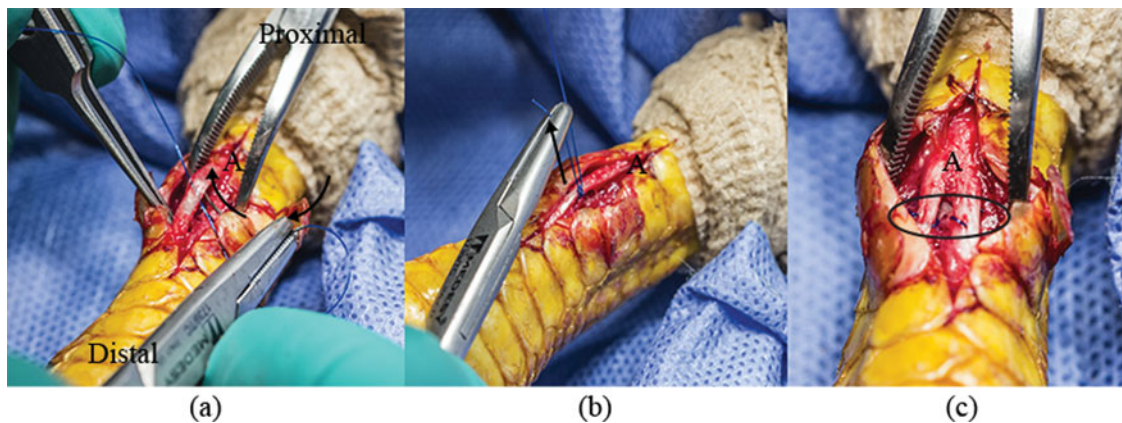

FIGURE 6   Suture-based surgery. The lateral branch of the EDL tendon was isolated using Bishop Harmon forceps at the point of bifurcation (A), and a simple interrupted suture with 5-0 prolene was placed longitudinally (a). Both the lateral and medial EDL tendon branches were sutured at a slight angle longitudinally with the square knots oriented on the deep surface of the tendons (b and c).
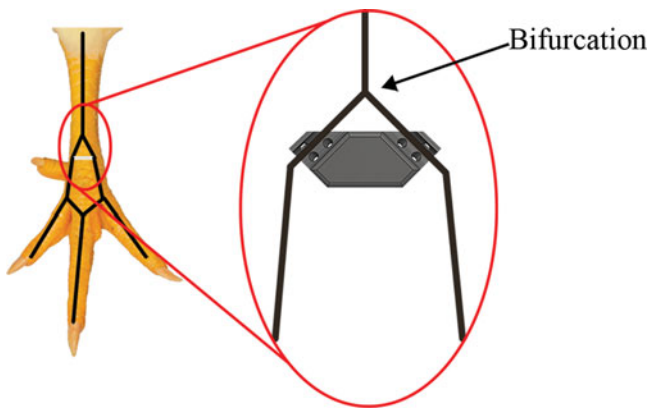
FIGURE 7   Schematic of the extensor digitorum longus tendon network (black outline) in the chicken leg with an implant placed just distal of the bifurcation.

FIGURE 8   The incision site of a male implanted chicken 4 days postoperative. Mild bruising and swelling was present with evidence of two scales lost. Skin was well apposed and healing appropriately.

underwent no surgical procedure. All birds were humanely euthanized between five and ten weeks postoperatively.

Surgical Anatomy

The medial spur of the left hindlimb was used as a landmark to identify the bifurcation of the EDL tendon. For the implant group chickens, the implant was placed just distal of the EDL tendon bifurcation (mean 8.50 ± 3.73 mm). For the sham group chickens, sutures were placed in a similar location in respect to the EDL tendon bifurcation. The EDL tendon anatomy schematic can be seen in Figure 7 with the depiction of where the implant was located. Anecdotally, the lateral tendon appeared larger than the medial tendon branch, and both tendon branches were subjectively more robust in males than females. Tendon mineralization was suspected in some but not all male chickens just distal to the EDL bifurcation, which was noted by the surgeon's ability to pass the needle through each tendon during placement of sutures. Tendons were surrounded by thin connective tissue. There were no vessels surrounding the bifurcation or proximal EDL branches that required ligation or cauterization.

Wound Healing

All twenty-two chickens were considered healed by Day 16 postoperatively due to the presence of keratinization (Figure 8). Varying degrees of serosanguinous discharge, swelling, bruising, erythema, and scale loss were noted in all chickens postoperatively. Scales were disrupted due to the dorsal midline incision. Mean scale loss for all chickens was 2.25 ± 0.29 scales. The implant group chickens (mean 2.81 ± 0.42 scales) experienced significantly more scale loss than the sham group (mean 1.56 ± 0.24 scales; $p = 0.025$).

Discharge was noted up to Day 16 postoperatively (mean 10.86 ± 0.72 days with a median time of 12 days). There was no significant difference in discharge duration between the implant group (mean 11.5 ± 0.84 days; median 12 days) and the sham group (mean 10.1 ± 1.22 days; median 10.5 days; $p = 0.342$).

Postoperative Complications

Minor postoperative complications were noted in all the animals that underwent surgery. This included seroma formation in all the chickens that underwent surgery, suspected surgical site infection in two chickens, and partial wound dehiscence in two chickens. Seromas were suspected based on the presence of varying degrees of soft tissue swelling with serosanguinous discharge. Seromas resolved within sixteen days postoperatively in all animals. Purulent discharge from the surgical site was noted in one animal in the implant group and one in the sham group on Day 3 and 7 postoperatively. Each incision was cleaned with betadine and saline aseptically and enrofloxacin was administered intramuscularly for an additional day. Purulent discharge was not noted at the subsequent bandage changes in both animals. Two chickens in the implant group experienced partial minor wound dehiscence. In each chicken, a 2- to 3-millimeter defect was noted along the incision line a few days postoperatively. The incision sites were cleaned with betadine and saline aseptically for two days. Both chickens healed without further complication.

TABLE 1 Postoperative characteristics of the implanted patients (n = 12). M = male, F = female; Y = yes, N = no; additional complications of seroma and infection were suspected based on clinical signs

Chicken ID No.	Sex	Implant Distance from Bifurcation (mm)	Drainage Duration (day)	Toe Knuckling	Additional complications
2	M	12.28	11	Y	Seroma
3	M	15.95	10	N	Seroma
4	M	14	12	Y	Seroma
6	M	8.67	16	Y	Seroma
8	M	7.84	6	Y	Seroma
10	M	7	15	Y	Seroma
12	F	7.15	8	Y	Seroma
14	F	8.85	14	Y	Seroma, infection
16	F	4.89	12	Y	Seroma
18	F	5.98	12	Y	Seroma
20	F	4.5	13	Y	Seroma, dehiscence
22	F	4.85	9	Y	Seroma, dehiscence
Mean		8.50	11.5		
Median		7.50	12		

TABLE 2 Postoperative characteristics of the sham patients (n = 10). M = male, F = female; Y = yes, N = no; additional complications of seroma and infection were suspected based on clinical signs

Chicken ID No.	Sex	Implant Distance from Bifurcation (mm)	Drainage Duration (day)	Toe Knuckling	Additional complications
5	M	—	14	N	Seroma
7	M	—	12	N	Seroma
9	M	—	6	N	Seroma
11	M	—	5	N	Seroma
13	F	—	15	N	Seroma
15	F	—	12	N	Seroma
17	F	—	14	N	Seroma
19	F	—	9	N	Seroma
21	F	—	5	Y	Seroma
23	F	—	9	N	Seroma, infection
Mean		—	10.1		
Median		—	10.5		

The only major complication noted was suspected fibrosis in 11 out of 22 (50%) chickens. This was clinically associated with an abnormal toe-knuckling gait. Chickens with "toe-knuckling" showed an intermittent inability to extend the digits during walking, most noticeably the third digit. This abnormality was seen in 10 (83.3%) chickens in the implant group and only 1 (10%) in the sham group. Chickens in the implant group experienced significantly more toe knuckling than the sham group (p = 0.001). Despite suspected fibrosis, chickens were still able to ambulate normally or only exhibited signs of mild lameness. Findings regarding the outcome of the chickens in both the implant and sham groups are summarized in Tables 1 and 2, respectively.

DISCUSSION

The current tendon transfer surgery for treating high median-ulnar nerve palsy only partially improves hand function. Specifically, the flexion of multiple fingers become coupled following surgery due to the direct suturing of the four finger flexor tendons to one wrist extensor muscle. This will prevent the fingers from naturally adapting to the object's shape when grasping objects [6]. This study uses the chicken model to present the in vivo validation of a new surgical technique for treating high median-ulnar nerve palsy. This paper particularly focuses on the anatomical aspects of the surgery and the clinical response to inserting the implant between the tendons. In combination with previous in vitro work of the implant that validated improved functionality, results from the present study showed promise in our work to developing a new tendon transfer surgery that creates a "differential mechanism" for median-ulnar palsy.

The surgical technique presented here allowed for a successful application of the novel passive mechanism implant in live chickens. The implant surgery was completed successfully in all chickens. There were no catastrophic complications during the perioperative period, and all chickens in both groups had acceptable functionality following surgery. Chickens with the EDL tendon implant healed similarly to chickens in the sham group. There were no differences in healing time between the implant and sham groups, and all incisions had healed within 16 days postoperatively. These results provide evidence that the proposed surgery is feasible when performed in a live animal and warrants further research in the search for better treatment options for high median-ulnar nerve palsy.

This study demonstrates the feasibility of the domestic chicken as an in vivo model for tendon research while contributing to the knowledge of chicken tendon anatomy. Previous work related to the chicken model primarily focuses on the digital flexor mechanism and anatomy [16], while here we present a surgical technique at the level of the tarsometatarsal EDL tendon. Domestic chickens were the chosen model because of their similarities to humans in pertinent anatomy including blood supply [17], flexor apparatus [16], and tendon healing [18, 19]. They are amenable to handling and are well-studied in terms of behavior, husbandry, and veterinary care. These features were further exemplified in our study where

all chickens tolerated handling for bandage changes and veterinary care. Moreover, all animals were highly food-motivated, which allowed for easy gait evaluation to detect for signs of lameness. Although tendon size may be a potential disadvantage of the chicken model [17], we noted more robust tendons in male chickens which may be considered for future studies in this model. In addition to similar flexor tendon anatomy and biomechanical properties [16, 20], these findings ultimately suggest that chickens are appropriate models for future research in new approaches to tendon transfer surgeries.

Disregarding suspected seroma formation, the only minor complications observed were suspected surgical site infection (SSI; 9%) and partial wound dehiscence (9%). Culture and sensitivity testing was not performed for the suspected infections in two chickens, which would have definitively diagnosed an infection. To the authors' knowledge, incidence of SSIs in birds or chickens have not been reported following tendon or other hindlimb surgery. Furthermore, no additional treatment was necessary following initial diagnosis and treatment. Further research with larger sample sizes and longer follow-up may glean more information on the incidence and effect of SSIs associated with this surgery. Both greater scale loss in the implant group and the presence of partial wound dehiscence in two chickens of the implant group are most likely attributable to the implant size. Both chickens with partial wound dehiscence were female and had marked skin tension due the implant and the smaller anatomy of the leg, specifically the smaller diameter of the lower hindlimb. This further illustrates the need for refinement in the implant design as well as potentially the selection of male chickens over females for their larger tendons and overall anatomy of the leg. Despite these minor complications reported, all incisions healed appropriately suggesting that they may not negatively impact overall functionality outcomes.

The main challenge in this study was the suspected tendon fibrosis associated with the surgery and implant. Adhesion formation is a significant concern with any tendon transfer surgery with or without an implant, particularly in the case of tendon transfer surgeries for combined peripheral nerve injuries [1]. Tendon adhesions cause decreased range of motion and loss of normal tendon gliding [21, 22]. Although this study did not evaluate histologic evidence of fibrosis, observation of "toe-knuckling" was presumptive for this clinically relevant complication. The implant group experienced a significantly higher rate of intermittent "toe knuckling" than the sham group, but we suspect that this abnormal gait was due to adhesion formation. Another possibility is the implant itself inhibiting normal tendon gliding. Histologic evaluation and other modalities of adhesion assessment such as a video-assisted gliding test or ultrasound might better quantify the implant's effects on adhesion

formation in future work [22]. We expect that with refinement to the surgical implant, both in terms of a slimmer, smoother physical profile and an addition of lubricious, non-fouling coatings, the incidence of "toe-knuckling" will decrease substantially.

Although chickens were encouraged to walk regularly following surgery, no physical therapy regimen was instituted. Postoperative motion has been shown to improve tendon healing in a chicken model [23], and early controlled passive motion may improve tendon healing efficiency as demonstrated in a chicken model [24]. Other studies have provided evidence for the benefits of postoperative synergistic motion in order to help prevent tendon adhesion formation in the canine model [25, 26]. Future studies will explore passive range of motion and other rehabilitation exercises to promote tendon healing and help limit adhesion formation.

Other limitations of the present study include sample size, lack of blinding procedures, and potential bias related to the surgeon's experience level performing a new surgery. Only one surgeon performed all the surgeries, but experience of the surgeon improved throughout the duration of the study, which may have contributed to the outcome. Although not statistically assessed, trends were not noted in healing time, complication rate, or lameness between animals earlier versus later in the study. The authors were not blinded to each cohort group during postoperative evaluation; however, this study did not evaluate subjective outcome measures. That being said, future studies looking at the clinical outcome will include a blinded study design to eliminate potential bias. As discussed, this pilot study was intended to validate the implants in a live animal model. As with any *in vivo* model, differences are to be expected with previous *in vitro* work and thus, adjustments to the implant and surgical technique are to be expected for future studies. Based on the degree of suspected fibrosis in the implant group, revisions to the surgical implant are necessary where the implant will include a smaller size, smoother edges and surface, and narrower angle for the tendon grooves. Overall, the results of this randomized, controlled, prospective study provided promising results in the development of a new surgical procedure and technique for high median-ulnar nerve palsy in a chicken model. A larger, similarly designed study is necessary to assess clinical outcome of animals undergoing the novel tendon transfer surgery that constructs a differential mechanism with the biological tendon network and an artificial implant.

DECLARATION OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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