Original Article

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# Morphological Changes in Flexor Tendon Adhesion Following Early Exercise After Tendon Repair

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**Summary:** Adhesion is a common complication following surgical repair of flexor tendons, resulting in the restriction of tendon gliding. We investigated the effect of early exercise on adhesion formation. To create an adhesion model, the proximal region of the second phalanx of the third toe in 4-month-old White Leghorn chickens was cut. The gliding side of the flexor digitorum profundus was hemiresected and the bony floor was crushed to enhance adhesion formation. The resected area was fixed in an extended position for 1, 2, or 3 weeks. Following 1, 2, or 3 weeks of active exercise, the chickens were sacrificed and morphological changes in the adhesions were assessed. In the 1- and 2-week fixed groups, 1, 2, or 3 weeks of active exercise resulted in mesotenon-like adhesion that was elastic and had no effect on tendon gliding. However, in the 3-week fixed group, a mature adhesion remained with limited change and tendon gliding was inhibited even after 3 weeks of active exercise. Thus, we concluded that adhesions become more elastic with early exercise within 2 weeks after tendon repair, but that adhesions following tendon repair tend not to show any further elastic changes when exercise is started 3 weeks after the repair.

**Keywords** flexor tendon, early exercise, adhesion, white leghorn, repair

## INTRODUCTION

Tendon adhesion, in which a healing tendon adheres to surrounding structures and restricts tendon gliding, is a common problem after tendon surgery. Many basic and clinical studies have been conducted to find ways to prevent adhesion following the surgical repair of the flexor tendons in the finger [1-3]. It has been reported that early exercise performed after the repair eliminates the existing adhesion and prevents further adhesion, thus ameliorating the restricted gliding of the tendon [4,5]. Tokita et al. [6] reported that, for sutured tendons, removing adhesions improved tendon gliding. They removed a small area of adhesion, which led to the invasion of the ruptured area by granulation tissue. The area was subsequently ruptured again before the maturation of the granulation tissue; repetition of this process produced an elastic, mesotenon-like adhesion, resulting in a vascularized tendon with good gliding. Umeda et al. [7] reported that, after tendon repair by suture of the peritenon, a loose and spindly vincula-like tissue formed, resulting in a tendon that moved smoothly during exercise. Peacock [8] suggested that gliding of the repaired tendon is facilitated by extending the length of the adhesion. To support this, he described the autopsy of a patient who had died several months after a tendon transplant. The patient's adhesion had lengthened, and the tendon was able to glide.

There have been no published reports of studies that investigated morphological changes in the adhesion of tendons following periods of early exercise of the adhesive regions. To assess any such morphological changes, we created an animal model of tendon

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Abbreviation: FDP, flexor digitorum profundus.

injury and adhesion using White Leghorn chickens. In our experimental model, we resected the flexor digitorum profundus (FDP) of the third toe, and then kept the toe in a free position for 3 weeks, after which the chicken was able to move the toe freely. Three weeks later, a corded (string-like) elastic adhesion could be observed in the autopsy on the proximal side of the torn FDP tendon (Fig. 1). We observed that exercise changed the elasticity of the adhesion and made it less rigid. Supported by this observation, we hypothesized that continuous exercise performed shortly after the surgical repair of the flexor tendon would improve tendon gliding. In the present *in vivo* study, therefore, we investigated the effects of early exercise on the adhesion of repaired tendons and considered its clinicopathological significance.

## MATERIALS AND METHODS

*Animals*

This study used 46 White Leghorn chickens aged 4 months, weighing 1.5–1.8 kg. The experimental procedures and the housing and care of the chickens complied with the guidelines of our institutional animal experimentation committee and with the national laws concerning the care and use of laboratory animals. The study protocol was reviewed by the Institutional Animal Care and Use Committee of Kurume University and approved by the President of Kurume University. All the animal experiments were conducted in compliance with the protocol reviewed by the Institutional Animal Care and Use Committee and approved by the President of Kurume University. Additionally, this trial was registered with the approval of the Ethics Committee of Epidemiological Studies of Kurume University Faculty of medicine. According to the study protocol, chickens were sacrificed by a 3 mL intravenous injection of thiopental sodium.

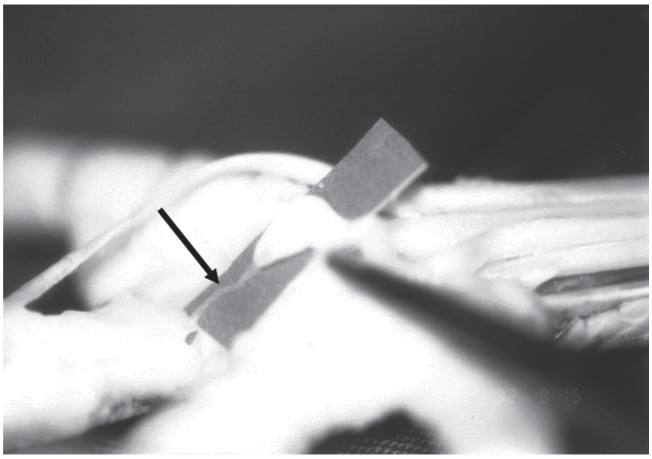

*Fig. 1.* The experimental model of adhesion in a White Leghorn chicken
Corded, elastic, mesotenon-like adhesion is observed at the end of the cut central flexor digitorum profundus (arrow).

*Study 1: Creating adhesion models*

To create the adhesion models, general anesthesia was provided to 6 chickens using a 20 mg/kg pentobarbital intramuscular administration with a nerve block using mepivacaine hydrochloride. Next, a small area of the ligamentous peritenon in each of the chickens was partially cut in the proximal region of the second phalange of the third toe (Fig. 2a). This area corresponds in the human hand to the region between the proximal two-thirds of the finger and the distal inch of the palm and is known to be problematic for adhesion formation; it is often referred to as “no man’s land.” Using a microscope, the gliding side of the FDP was hemiresected without resection of the flexor digitorum superficialis. The bony floor was injured using sharp-force with a scalpel to enhance the formation of adhesion. Following these procedures, the third toe was fitted with a device made from lightweight Surlyn® resin (Dow Chemicals, Midland, MI, USA); this fixed it in an extended position without stressing the chicken (Fig. 2b). The device pressed the hemiresected area and the bony floor tightly together to enhance adhesion formation. Its light-weight nature eliminated problems of cast breakage, limping, and debility caused by cast weight, which has been observed in studies that used plaster cast fixation. The toe was fixed in place for 1-, 2-, or 3-weeks. After sacrificing the animals, the adhesion conditions of the hemiresected area and the bony floor were assessed.

*Study 2: The effects of exercise*

Using the adhesion models designed in Study 1, the effects of exercise for a 1-, 2-, or 3-week period were investigated. During this period, the chickens were allowed to be active and the third toe of each chicken was passively exercised from maximum flexion to maximum extension 100-times each day. In total, 4 chickens were used for each combination of 1, 2, or 3 weeks of fixation and 1, 2, or 3 weeks of exercise, thus requiring a total of 46 chickens (Table 1). The animals were sacrificed and morphological changes in the tendon adhesion were assessed.

*Study 3: Bilateral hemiresection*

Using the same method as described for Study 1, bilateral hemiresection of the FDP was performed on

4 additional chickens. The right leg was fixed for 1 week followed by a 3-week period of exercise, while the left leg was fixed for 4 weeks. Following this 4-week period, the animals were sacrificed, and morphological changes in tendon adhesion were assessed.

*Statistical analysis*

All statistical analyses were conducted using STAR v. 9.70j (kisnet.or.jp/nappa/software/star/freq/chisq_ixj.htm). The chi-square test was used for all statistical analysis and $P<0.05$ was considered significant.

## RESULTS

*Study 1: Creating adhesion models*

In the 1-week fixed model, reddish-brown juvenile granulation tissue invaded the hemi-resected area, and loose adhesion was formed (Fig. 2c). In the 2-week fixed model, adhesion formed over the entire hemiresected area (Fig. 2d). In the 3-week fixed model, mature adhesion and revascularization from the bony floor were observed (Fig. 2e).

*Study 2: The effects of exercise*

The effects of exercise according to duration of fixation are summarized in Table 2. One week of exer-

TABLE 1.
*Number of chickens in each of the three studies*

| | | Number of chickens |
|---|---|---|
| Study 1 (Adhesion model) | | |
| | 1-week fixation | 2 |
| | 2-week fixation | 2 |
| | 3-week fixation | 2 |
| Study 2 (Effects of exercise) | | |
| | 1-week fixation | 4 |
| 1-week exercise | 2-week fixation | 4 |
| | 3-week fixation | 4 |
| | 1-week fixation | 4 |
| 2-weeks exercise | 2-week fixation | 4 |
| | 3-week fixation | 4 |
| | 1-week fixation | 4 |
| 3-weeks exercise | 2-week fixation | 4 |
| | 3-week fixation | 4 |
| Study 3 (Bilateral hemiresection) | | |
| 3-weeks exercise | 1-week fixation | 4 |
| No exercise | 4-week fixation | 4[a] |

[a] Four chickens in total were used in Study 3.

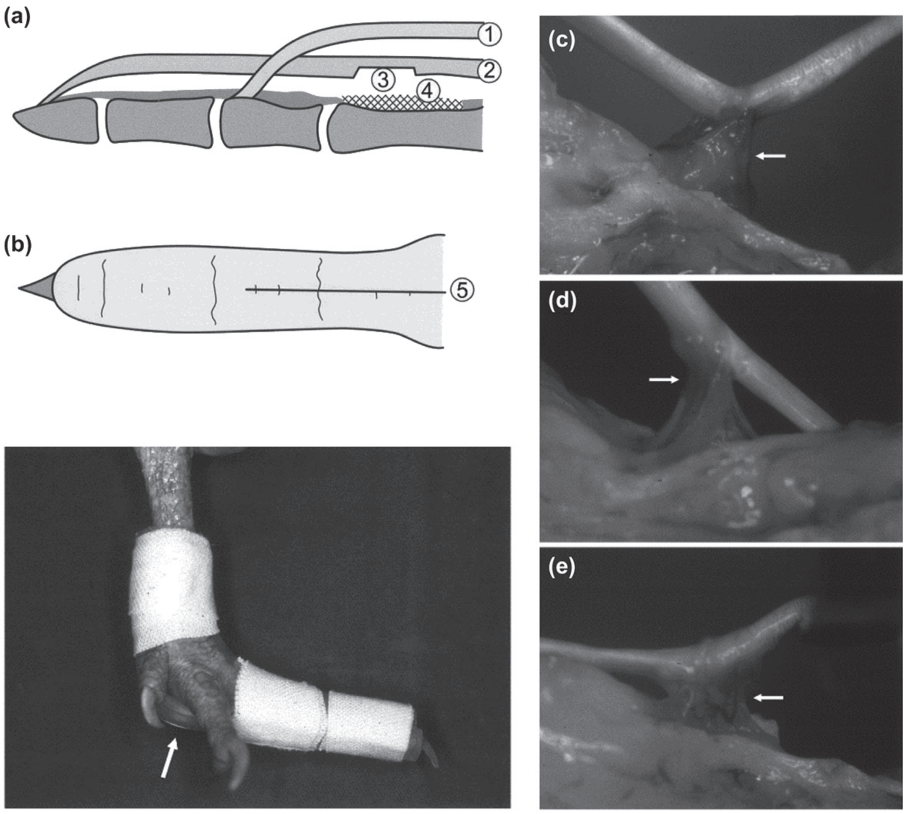


*Fig. 2.* The adhesion model in White Leghorn chickens
(a) The gliding side of the flexor digitorum profundus (FDP) is hemiresected in the proximal region of the second phalange and the bony floor is crushed. Following this procedure, the third toe is fixed in an extended position. ① The flexor digitorum superficialis. ② The flexor digitorum profundus. ③ The hemiresected area. ④ The crushed area. ⑤ The longitudinal incision of the second phalange. (b) The light-weight device for maintaining fixation of the toe in an extended position, developed using Surlyn® resin. (c) The adhesion model is fixed for 1-week. Reddish-brown juvenile granulation tissue invades the hemiresected area and loose adhesion is formed (arrow). (d) The adhesion model fixed for 2-weeks. Adhesion is formed over the entire hemiresected area (arrow). (e) The adhesion model fixed for 3-weeks. Mature adhesion and revascularization from the bony floor is observed (arrow).

cise loosened the adhesion in the hemiresected area in both the 1-week and 2-week fixed groups (Fig. 3a and b). This was observed both histologically and macroscopically, suggesting that the adhesion itself had been stretched by continuous exercise resulting in elasticity. Strong adhesion remained in the 3-week fixed group, and few changes were observed (Fig. 3c).

Two-weeks of exercise loosened the adhesions further in both the 1-week and 2-week fixed groups (Fig. 4a and b). In one of the 1-week fixed group chickens, the adhesion completely disappeared. However, in the 3-week fixed group, the mature adhesion remained even after the 2-week period of exercise (Fig. 4c).

Three weeks of exercise resulted in mesotenon-like adhesions in the 1-week and 2-week fixed groups (Fig. 5a and b). As a result, the adhesions were elastic and had no effect on tendon gliding. The complete disappearance of an adhesion was observed in only one of the chickens. In the 3-week fixed group, there were few changes in adhesion even after a 3-week period of active exercise, with the mature adhesion remaining and gliding in the tendon still inhibited (Fig. 5c). We observed tears in the tendon during exercise in 30% of the chickens that exercised for 3-weeks.

TABLE 2.
*Morphological changes in adhesion*

| | | Elastic | Rigid |
|---|---|---|---|
| Study 2 (Effects of exercise) | | | |
| | 1-week fixation | 4 | 0 |
| 1-week exercise | 2-week fixation | 3 | 1 |
| | 3-week fixation | 0 | 4 |
| * p < 0.01 | | | |
| | 1-week fixation | 4† | 0 |
| 2-weeks exercise | 2-week fixation | 3 | 1 |
| | 3-week fixation | 0 | 4 |
| * p < 0.01 | | | |
| | 1-week fixation | 4 | 0 |
| 3-weeks exercise | 2-week fixation | 4 | 0 |
| | 3-week fixation | 0 | 4 |
| * p < 0.01 | | | |
| Study 3 (Bilateral hemiresection) | | | |
| 3-weeks exercise | 1-week fixation | 4 | 0 |
| No exercise | 4-week fixation | 0 | 4 |
| * p < 0.01 | | | |

† One adhesion disappeared.
* p < 0.01 by chi-square test

*Study 3: Bilateral hemiresection*

In the 4 chickens that underwent bilateral hemiresection, the right leg, which was fixed for 1-week and then subjected to a 3-week period of exercise, exhib-

(a) (b) (c)

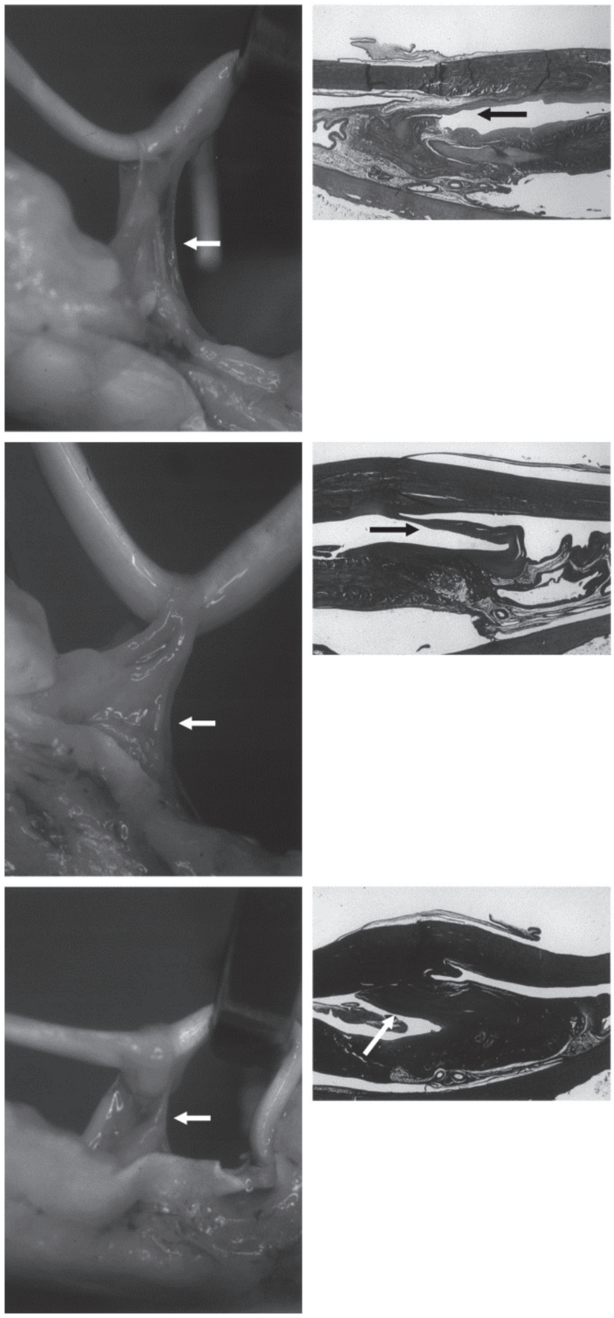

*Fig. 3.* The effects on adhesion from 1-week of early exercise
(a) Following 1-week of fixation, a 1-week period of continuous exercise resulted in greater elasticity of the adhesion. (b) Following 2-weeks of fixation, a 1-week period of continuous exercise resulted in greater elasticity of the adhesion. (c) In the 3-week fixed model, strong adhesion remained following 1-week of exercise.

ited an elastic adhesion that allowed tendon gliding (Fig. 6a). However, the left leg, fixed for 4-weeks with no exercise, showed strong adhesion between the tendon and the bony floor, which inhibited tendon gliding (Fig. 6b).

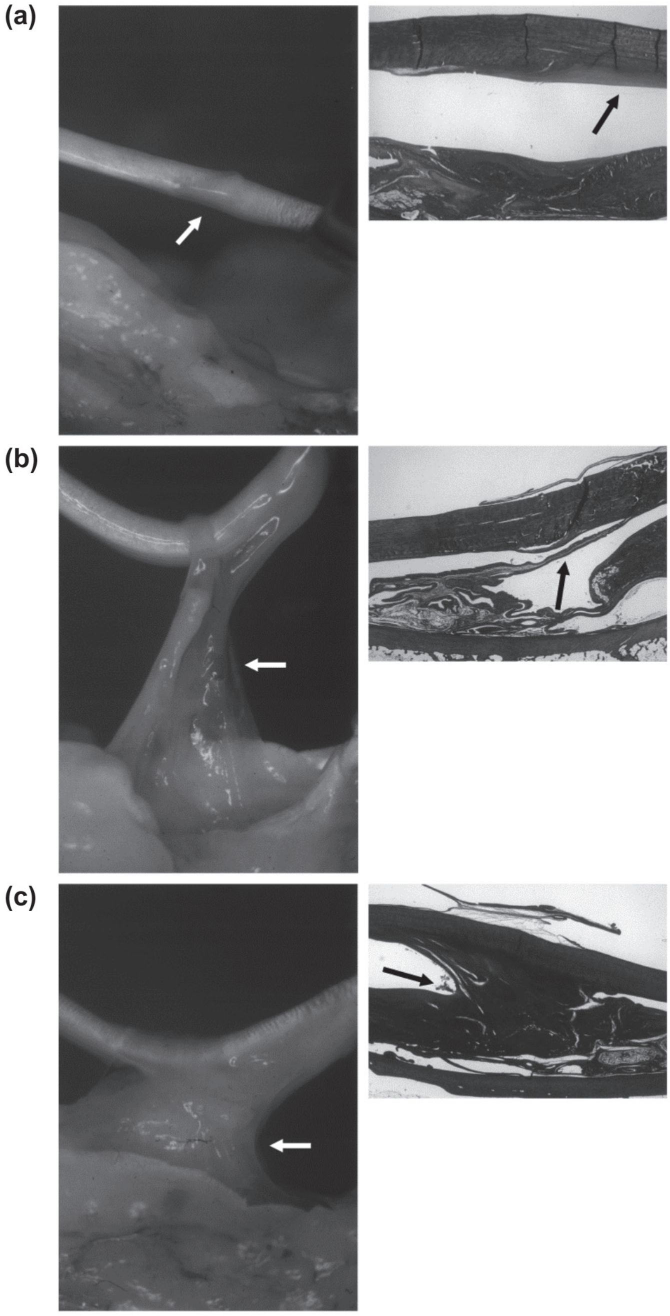

*Fig. 4.* The effects on adhesion from 2-weeks of early exercise
(a) In the 1-week fixed model, no adhesion was observed following 2-weeks of exercise. (b) In the 2-week fixed model, adhesion is loosened following 2-weeks of exercise. (c) In the 3-week fixed model, mature adhesion remained following 2-weeks of exercise.

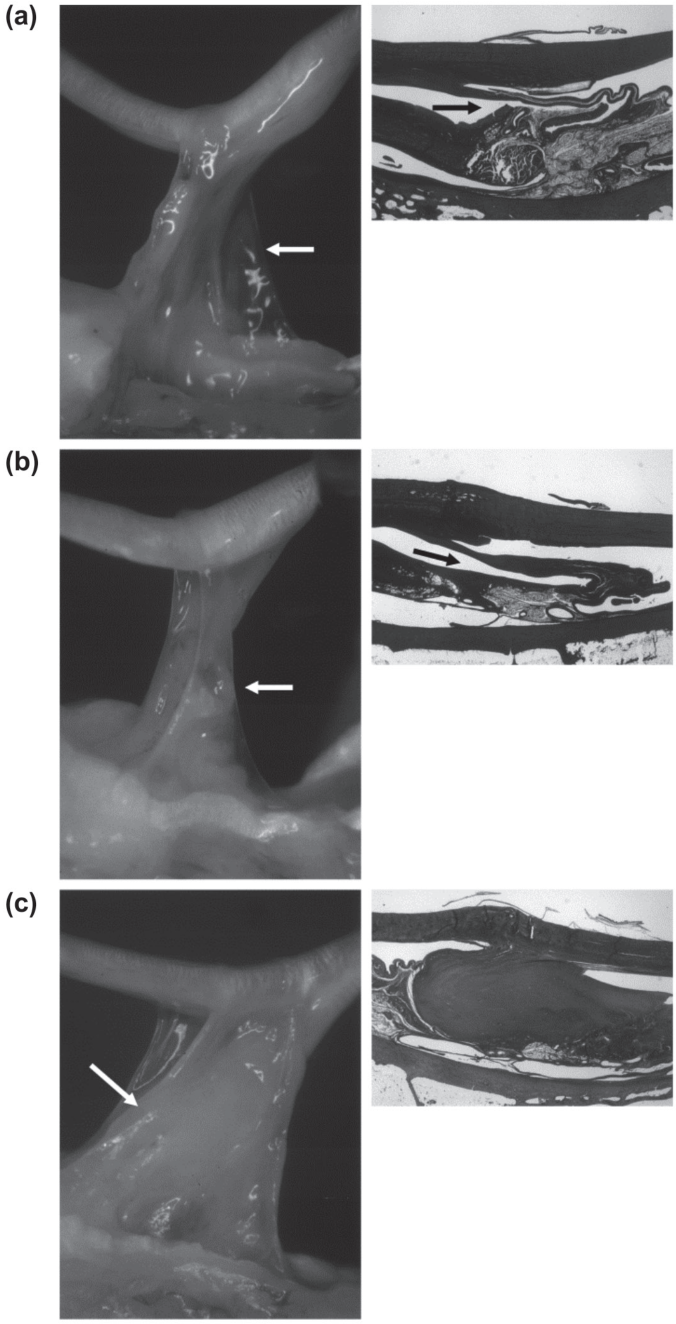

*Fig. 5.* The effects on adhesion from 3-weeks of early exercise
(a) In the 1-week fixed model, adhesion with mesotenon-like properties and little effect on tendon gliding is observed following a 3-week period of exercise. (b) In the 2-week fixed model, adhesion with mesotenon-like properties and little effect on tendon gliding is again observed following a 3-week period of exercise. (c) In the 3-week fixed model, mature adhesion remains, inhibiting tendon gliding, even after 3-weeks of exercise.

## DISCUSSION AND CONCLUSION

In this study, we hypothesized that early exercise after surgical tendon repair would loosen the adhesion between the flexor tendon and the bony floor, leading to morphological changes that produce a mesotenon-like elastic adhesion. However, we have found no morphologic or histologic reports to verify this. Recent progress in suture methods has allowed early exercise after repairs of the flexor tendon [9-13]. In a preliminary experiment using chickens, we confirmed that exercise did not cause any re-rupture of the tendon when approximately 50% of the gliding side of the tendon was microscopically hemiresected and the resected area then fixed for 1, 2, or 3 weeks. We have devised a fixation method that results in strong adhesions similar to those observed after the tendon has completely ruptured and sutured. While the effects of early exercise on the hemiresected tendon model may differ from those in actual clinical cases, the method used in Study 1, which used a hemiresected tendon without re-rupture and the device for fixation, produced adhesions the same as or similar to that formed between a sutured area and the bony floor after full resection. Yamamoto et al. [14] reported that early exercise enhanced revascularization and the connective tissue response in the sutured area, increasing adhesion and inflammation and prolonging the recovery period when compared to a resting approach. Mason and Allen [15] reported similar results. Yamamoto et al. [16] reported that passive exercise in the early stage after surgery caused an inflammatory reaction, enhanced collagen neogenesis, and reduced adhesion. In the present study, early exercise caused adhesions between the hemiresected FDP and the bony floor, formed following 1 and 2 weeks of postoperative fixation, developing into macroscopically and histologically elastic and mesotenon-like adhesions. This process did not inhibit tendon gliding and did not result in increased adhesion. Yamaya [17] proposed that tensile strength remained weak during the 2 weeks following surgery and that tight adhesion formed by 5 weeks following surgery. Thus, the optimal fixation period would be 3–4 weeks following surgery. This was apparently because of sufficient flexion of the dactylus by pulling the FDP on the proximal side of the adhesion. However, the results of our study suggest that a postoperative 3-week fixation period results in the formation of mature adhesion and little morphological change in the adhesion would be macroscopically or

(a)

(b)

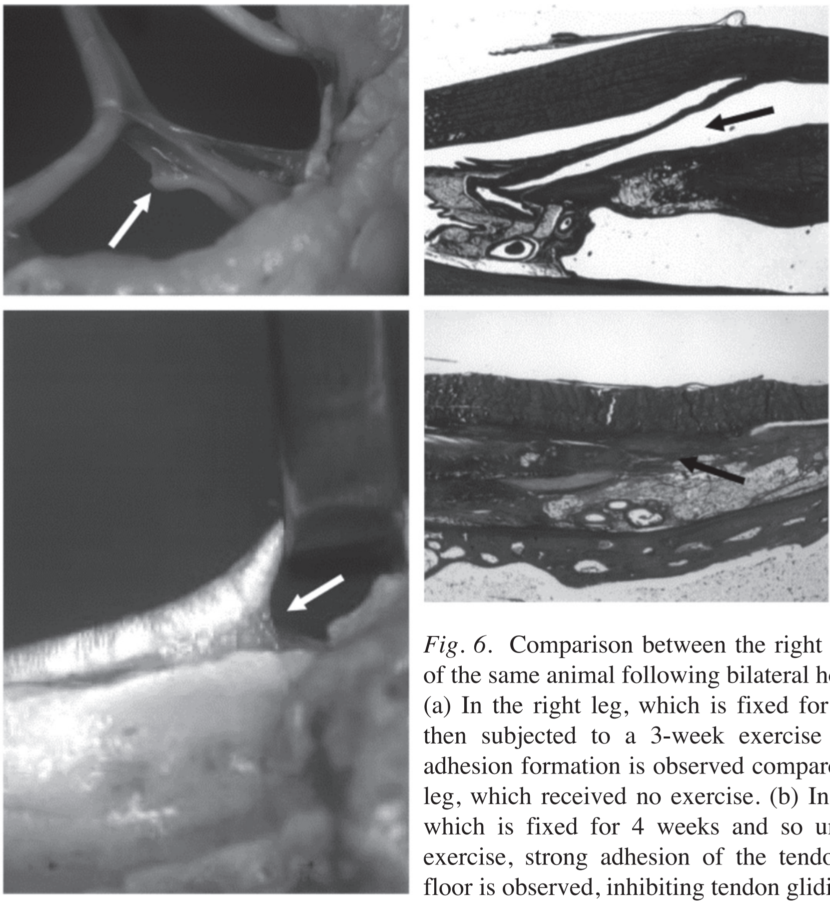

*Fig. 6.* Comparison between the right and left legs of the same animal following bilateral hemiresection (a) In the right leg, which is fixed for 1-week and then subjected to a 3-week exercise period, less adhesion formation is observed compared to the left leg, which received no exercise. (b) In the left leg, which is fixed for 4 weeks and so underwent no exercise, strong adhesion of the tendon and bony floor is observed, inhibiting tendon gliding.

histologically observed after this period, with no improvement in tendon gliding. As a result, adhesions within 2-weeks after tendon repair tend to develop elastic and mesotenon-like characteristics with early exercise. Progress in tenorrhaphy to allow early exercise has recently been reported [18-20]. This can be useful for improving tendon gliding following surgical repair. Chen et al. [21] reported that, on the 21st day after surgery, adhesions could not be fully released by a full range of FDP flexion. The development of suturing methods and biomaterials that can tolerate early exercise within the first 2-weeks after surgery may allow for the prevention and correction of tendon adhesion, resulting in a greater range of movement.

In conclusion, the results of this *in vivo* study suggest that adhesions become more elastic with early exercise within 2 weeks after tendon repair, but that adhesions following tendon repair tend not to show any further elastic changes when exercise is started 3 weeks after the repair. It can be inferred that new suturing methods and early exercise can be clinically successful, supported by the fact that if exercise is performed within 2 weeks, the adhesion becomes elastic and does not inhibit tendon gliding.

CONFLICT OF INTEREST: The authors declare that they have no conflicts of interest.

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