Contributions of the ischiofemoral ligament, iliofemoral ligament, and conjoined tendon to hip stability after total hip arthroplasty: a cadaveric study

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Running title: Joint stability in hip arthroplasty

Author contributions:

All authors contributed to the study conception and design. Material preparation was done by YT and YT. Surgical procedures for cadaver specimen were performed by YT, TG, JI, KW, and DH. The first draft of the manuscript was written by YT and was revised by TG and KS. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Abstract

An adequate soft tissue balance is important in total hip arthroplasty (THA). This study assessed the contribution of the iliofemoral ligament, ischiofemoral ligament, and conjoined tendon to the range of hip rotation after THA and hip stability in response to axial traction. THA was performed in eight fresh-frozen cadaveric specimens via an anterolateral approach using a navigation system. The ischiofemoral ligament, the medial arm of the iliofemoral ligament, and the conjoined tendon were resected in that order. The ranges of external and internal rotation and the amount of movement of the femoral head in response to axial traction were measured with the hip in 10° of extension, the neutral position, and in 10°, 30°, and 60° of flexion. Resection of the medial arm of the iliofemoral ligament significantly increased the range of external rotation in 10° of extension, the neutral position, and in 10°, 30°, and 60° of flexion. The conjoined tendon was the most important inhibitor of internal rotation from 10° of extension to 30° of flexion. Although each single element had a minor role in stabilizing the hip when axial traction was applied, resection of two or more elements significantly affected joint stability. The iliofemoral ligament and conjoined tendon are the main inhibitors of external rotation and internal rotation respectively when THA is performed using an anterior or anterolateral approach. Resection of two or more elements could greatly affect hip stability when axial traction is applied.

Keywords: total hip replacement, anterolateral approach, dislocation, hip capsule, short external rotators

Introduction

Appropriate management of soft tissue is quite important in total hip arthroplasty (THA), and there is increasing interest in the role of the capsular ligaments in joint stability after THA [1-4]. The main components of the hip capsule are the iliofemoral, ischiofemoral, and pubofemoral ligaments [3-8]. The iliofemoral and ischiofemoral ligaments are thought to be the major anatomic elements of the hip capsule and the dominant restraints for external and internal rotation, respectively [1,3,9-12]. Intraoperative damage to these capsular ligaments might increase the risk of an excessive range of motion of the hip, which is associated with dislocation and/or impingement. The short external rotators may also be important stabilizers of the hip joint, but selective resection of the conjoined tendon is sometimes needed for correct implantation of the stem when THA is performed using an anterior or anterolateral approach [13-15]. A major concern for surgeons is the effect of the resection of the capsular ligaments or conjoined tendon for postoperative joint stability.

Although hip joint stability has been investigated in several studies, most of them were performed using skeletonized cadaveric hip joints with complete removal of the muscle tissue [1,3,9,12,16]. The fresh-frozen whole-body cadaver model is ideal for evaluating hip joint stability after THA because it allows examination of various potentially important contributors to stability, including alignment of the implant, the capsular ligaments, and the muscles around the hip.

The purpose of this study was to evaluate the contribution of the ischiofemoral and iliofemoral ligaments and conjoined tendon to the range of motion of the prosthetic hip in external and internal rotation after THA via an anterolateral muscle-sparing approach. In addition, the resistance of the prosthetic joint to axial separation was also measured.

Methods

Subjects

This study was approved by our institutional review board and performed in line with the principles of the Declaration of Helsinki. Written informed consent is routinely obtained from all cadaveric donors and their families when they donate their bodies to the institution for research purposes. Eight hips of 8 fresh-frozen cadavers (5 male, 3 female) were used. Mean age at the time of death was 78.1 years (range, 69–89). All cadaveric specimens were macroscopically intact without gross deformity or obvious joint contracture. Evaluation of osseous morphology by computed tomography (CT) found no evidence of osteoarthritic changes, such as joint space narrowing, osteophytes, deformity of the femoral head, or previous hip surgery, in any of the specimens. All cadavers were stored at -20°C until examination. At the time of study, each specimen had been thawed for 48 h at 21°C (room temperature).

Surgical procedure and experimental evaluation of joint motion and distraction resistance.

We performed THA in the supine position with a Trident cup and Accolade II femoral hip stem (Stryker, Mahwah, NJ) using a standard anterolateral approach. Briefly, we made a skin incision at the anterior border of the gluteus medius muscle and accessed the hip capsule through the interval between the tensor fascia lata and gluteus medius muscle. The lateral arm of the iliofemoral ligament was resected to expose the hip joint (Fig. 1a). The ischiofemoral ligament and the medial arm of the iliofemoral ligament were preserved. We used a CT-based navigation system (Stryker, Freiburg, Germany) for preoperative planning, implantation, and postoperative motion analysis of the hip joint (Fig. 2). Registration of the navigation system at the pelvis and femur was performed according to the manufacturer's protocol. Preoperative CT images in DICOM format were transferred to the three-dimensional planning station. Pelvic coordinates were determined by identifying 8 landmarks, including the anterior superior iliac spine, pubic tubercle, and ischium on both sides, the pubic symphysis, and the sacral midplane. Femoral coordinates were determined by identifying 12 landmarks on both femurs, including the center of the femoral head, the piriformis fossa, the proximal posterior aspect of the femur, the posterior aspect of the medial condyle and lateral condyle, and the center of the knee. During the operation, 4-mm apex pins were inserted into the pelvic rim and distal portion of the femur and the active marker tracker was firmly connected to the pins (Fig. 2). After the hip joint was exposed, initial paired-point matching registration was performed by digitizing the four bony landmarks determined during the preoperative planning. Surface matching registration was then performed on the surfaces of the pelvis and femur [17] (Fig. 3). When registration was complete, we checked the root mean square values between the surface model and the digitized points and considered values < 1 mm to be acceptable. Once registered, a series of examinations could be performed using the same coordinate system in the pelvis and femur. We resected the femoral neck based on the position indicated by the navigation system. The acetabulum was then under-reamed by 1 mm and the trial cup was inserted using the press-fit technique. Basically, the target cup placement angles were 40° of anatomic inclination and 25° of anatomic anteversion. Finally, femoral rasping was performed. The final rasp was used for the examination. In each case, we used a trial head with a diameter of 32 mm, and the neck size was chosen so that the leg-length discrepancy after THA was within 5 mm of that on the contralateral side according to the navigation system to avoid an extreme change in soft tissue tension after surgery. At the time of implantation, the final cup and stem data (e.g., size, location, and alignment) were recorded, after which ROM and movement of the center of the prosthetic femoral head could be monitored in real time (Figs. 4 and 5). After placement of the trial implant, we assessed the range of external rotation, range of internal rotation, and amount of movement of the prosthetic femoral head in response to axial traction. Each assessment was performed in 10° of hip extension, the neutral position, and 10°, 30°, and 60° of hip flexion. During the assessments of external and internal rotation, the hip position was confirmed by the navigation system and the hip abduction and adduction angles were kept in the neutral position, defined when the anatomic axis of the femur was parallel to the midline of the body (Fig. 4). During assessment of movement of the prosthetic femoral head in response to axial traction on the leg, the position of the hip was confirmed by the navigation system to be neutral in terms of the abduction and rotation angles (Fig. 5). The hip was kept in a stable flexed position by placing pillows between the femur and the surgical table (Fig. 5). When measuring the range of rotation, we reduced dispersion by manually applying a fixed rotation torque of 20 Nm using a dynamometer (Fig. 4). The separation distance in the axial direction was defined as the amount of movement between the prosthetic femoral head and the trial insert under 250 N of manual traction using a spring scale (Fig. 5). This value of traction force was set with reference to a similar study [18]. Movement of the femoral head by < 5 mm could not be displayed because of the limitations of the navigation system so was measured manually by marking the position of the femoral head before and after traction using an electronic caliper (measurement range, 0.01–150 mm). Resection of the lateral arm of the iliofemoral ligament only was defined as the “intact” condition (initial step) (Fig. 1b). We then established three further conditions by resecting the soft tissues surrounding the hip joint in the following order to simulate the anterolateral approach: (1) the ischiofemoral ligament (defined as “ischiofemoral ligament resection”); (2) the medial arm of the iliofemoral ligament (defined as “iliofemoral ligament resection”); and (3) the conjoined tendon (defined as “conjoined tendon resection”). We then measured the range of hip internal and external rotation, and amount of movement of the prosthetic femoral head when distraction force was applied under each hip flexion angle. All measurements were performed twice by the same senior surgeon and the results are shown as the average of two measurements.

Statistical analysis

Data were analyzed using repeated-measures analysis of variance with a post hoc test using the Tukey method in each setting. Given the small number of subjects, a post-hoc calculation of effect size and statistical power was performed using G*Power version 3.1.9.7 software. Based on the calculated effect size, the statistical power of each measurement was over 0.8, indicating that 8 specimens would be sufficient to detect statistically significant differences in internal rotation, external rotation, and amount of movement of the femoral head. All statistical analyses were performed using SPSS software (version 24.0; IBM Corp., Armonk, NY, USA). A P-value < .05 was considered statistically significant. The intraclass correlation coefficients indicated perfect intra-examiner reproducibility (0.99 for range of rotation and 0.98 for amount of movement of the femoral head).

Results

Range of external rotation

The changes in range of external rotation in each resection step are summarized in Table 1 and Fig. 6. When the iliofemoral ligament was resected, the mean amount of external rotation increased by 15.1° in 10° of extension, 16.4° in the neutral position, 8.2° in 10° of flexion, 3.4° in 30° of flexion, and 3.5° in 60° of flexion, and statistically significant differences between before and after iliofemoral ligament resection were observed in 10° of extension (P = .012), the neutral position (P < .01), and 10° of flexion (P< .01). There were small but steady increases in external rotation at the time of the ischiofemoral ligament and conjoined tendon resection steps in all hip positions, with no significant differences. When the ischiofemoral and iliofemoral ligaments were resected, the mean range of external rotation increased by 18.2° in 10° of extension, 18.7° in the neutral position, 12.0° in 10° of flexion, 3.7° in 30° of flexion, and 5.5° in 60° of flexion. The P-value was < .01 for all hip positions except for 30° of flexion (P = .07). When the iliofemoral ligaments and conjoint tendon were resected, the mean range of external rotation increased by 20.6° in 10° of extension, 17.3° in the neutral position, 12.5° in 10° of flexion, 6.9° in 30° of flexion, and 7.5° in 60° of flexion. These increases were statistically significant (P < .01) in all hip positions. When all three elements were resected, the mean range of external rotation increased by 23.7° in 10° of extension, 19.6° in the neutral position, 16.3° in 10° of flexion, 7.2° in 30° of flexion, and 9.5° in 60° of flexion. The increases were statistically significant (P < .01) in all hip positions.

Range of internal rotation

The changes in range of internal rotation in each step are summarized in Table 2 and Fig. 7. When the ischiofemoral ligament was resected, the mean range of internal rotation increased by 3.4° in 10° of extension, 6.3° in the neutral position, 6.7° in 10° of flexion, 7.6° in 30° of flexion, and 5.5° in 60° of flexion. Statistically significance was observed only in 10° of extension ($P = .039$). When the iliofemoral ligament was resected, the mean change in range of internal rotation was small and not statistically significant in any hip position. When the conjoined tendon was resected, the mean range of internal rotation increased by 6.0° in 10° of extension, 12.0° in the neutral position, 13.0° in 10° of flexion, 12.3° in 30° of flexion, and 4.4° in 60° of flexion. Resection of the conjoined tendon resulted in a significant increase in the range of internal rotation except in 60° of flexion ($P = .569$). When the ischiofemoral and iliofemoral ligaments were resected, the mean range of internal rotation increased by 8.1° in 10° of extension ($P < .01$), 9.2° the in neutral position ($P = .101$), 10.6° in 10° of flexion ($P = .079$), 10.8° in 30° of flexion ($P = .053$), and 10.1° in 60° of flexion ($P < .01$). There was a significant increase in range of internal rotation in 10° of extension and in 60° of flexion. When the iliofemoral ligament and conjoined tendon were resected, the mean range of internal rotation increased by 8.7° in 10° of extension, 14.9° in the neutral position, 16.9° in 10° of flexion, 15.5° in 30° of flexion, and 9.0° in 60° of flexion. The P-value was $< .01$ for all hip positions except for 60° of flexion ($P = .061$). When all three elements were resected, the mean range of internal rotation increased by 14.1° in 10° of extension, 21.2° in the neutral position, 23.6° in 10° of flexion, 23.1° in 30° of flexion, and 14.5° in 60° of flexion. The increases were statistically significant ($P < .01$) for all hip positions.

Amount of movement of the prosthetic femoral head when distraction force was applied

The results for amount of movement of the prosthetic femoral head during axial traction are summarized in Table 3 and Fig. 8. The increase in movement of the prosthetic femoral head was minor after resection of any single element in all hip positions. A significant increase was observed only at 30° of hip flexion after resection of the iliofemoral ligament (P = .011). When the ischiofemoral and iliofemoral ligaments were resected, movement of the prosthetic femoral head increased by a mean of 3.2 mm in 10° of extension, 4.6 mm in the neutral position, 3.8 mm in 10° of flexion, 4.9 mm in 30° of flexion, and 5.0 mm in 60° of flexion. The increase in movement compared with the "intact" condition was significant in all hip positions (P < .01) except in 60° of flexion (P = .055). When the iliofemoral ligament and conjoined tendon were resected, movement of the prosthetic femoral head increased by a mean of 2.9 mm in 10° of extension, 4.2 mm in the neutral position, 4.6 mm in 10° of flexion, 3.7 mm in 30° of flexion, and 2.8 mm in 60° of flexion. When compared with the "ischiofemoral ligament resection" condition, the increase in movement was significant in 10° of extension (P < .01), in the neutral position (P < .01), in 10° of flexion (P < .01), and in 30° of flexion (P = .017) but not in 60° of flexion (P = .451). When all three elements were resected, movement of the femoral head increased by a mean of 4.0 mm in 10° of extension, 4.2 mm in the neutral position, 6.1 mm in 10° of flexion, 6.8 mm in 30° of flexion, and 4.9 mm in 60° of flexion. When compared with the "intact" condition, the difference was significant in all hip positions (P < .01) except in 60° of flexion (P = .063).

Discussion

In this study, we evaluated the contributions of the ischiofemoral ligament, the iliofemoral ligament, and the conjoined tendon to the range of motion of the prosthetic hip in external and internal rotation. The resistance of the prosthetic joint to axial separation was also measured. Resection of the iliofemoral ligament resulted in a marked increase in external rotation from 10° of extension to 10° of flexion. There was a steady increase in the range of internal rotation with each step. Resection of the conjoined tendon had a particularly marked effect on internal rotation from 10° of extension to 30° of flexion. Resection of two or more elements led to a significant increase in the amount of movement of the femoral head when axial leg traction was applied in all hip positions except for 60° of flexion.

The iliofemoral ligament has been reported to have a significant role in limiting external rotation and anterior translation of the femur [9, 16]. Furthermore, Martin et al. found that the medial arm of the iliofemoral ligament had the greatest ability to inhibit external rotation of the hip in extension [3] while Hidaka et al. found that external rotation with extension placed a high strain on the medial arm of the iliofemoral ligament [7]. In the present study, there was a marked increase in external rotation from 10° of extension to 10° of flexion but not in 30° or 60° of hip flexion after resection of the medial arm of the iliofemoral ligament, possibly because the function of this ligament was limited as a result of relaxation of the anterior aspect of the capsule in more than 30° of hip flexion. Our finding that the iliofemoral ligament is important in preventing excessive external rotation in extension (where there is a risk of anterior dislocation) is consistent with previous reports. Therefore, preservation of the medial arm of the iliofemoral ligament is likely to be important in decreasing the risk of postoperative anterior dislocation.

Our study findings also indicate that the conjoined tendon has the strongest influence on internal rotation. The range of internal rotation was significantly increased by resection of the conjoined tendon in each hip position except at 60° of hip flexion. Other reports have suggested that the ischiofemoral ligament is the most important inhibitor of internal rotation with a native head size [3, 9]. However, those studies focused on the function of the capsular ligaments in skeletonized cadaveric hips that only preserved the capsule and did not evaluate the conjoined tendon. Safran et al. assessed the contribution of peri-articular soft tissues to the kinematics and stability of the hip and concluded that the kinematics of the hip was influenced by peri-acetabular soft tissue; specifically that range of motion increases with removal of increasing amounts of those tissues [19]. It should be borne in mind that data obtained from skeletonized cadavers may differ from those in a clinical setting. We believe that the effect of soft tissues on range of motion at the hip is better studied in whole-body cadavers with intact muscle than in skeletonized cadavers. In the present study, the ischiofemoral ligament seemed to be the second most important inhibitor of internal rotation after the conjoined tendon. The range of internal rotation was about 1.3 times greater after resection of the ischiofemoral ligament from 10° of extension to 30° of flexion. However, no statistically significant inhibition of internal rotation could be identified at 60° of flexion; in this position, the amount of change in internal rotation was relatively small in comparison with other flexion angles. These findings suggest that the tension on other tissues, such as the gluteal muscles or other short external rotators, becomes stronger at 60° of hip flexion [20].

The stability of the hip joint when axial traction is applied is thought to be important, and separation between the femoral head and acetabular insert is often observed during the swing phase of walking and might contribute to increased wear after THA [21]. Several biomechanics studies using cadaveric hip joints have indicated that the hip capsule is a significant stabilizer when axial traction is applied [18, 21]. Takao et al. found that the separation between the femoral head and acetabulum during axial leg traction was significantly increased after circumferential resection simulating THA performed by an anterior approach but remained unchanged by stepwise resection of the piriformis, conjoined tendon, and external obturator [18]. We also found a significant increase in the amount of movement of the femoral head when axial traction was applied after resection of both the ischiofemoral and iliofemoral ligaments. Therefore, in addition to resection of the lateral arm of the iliofemoral ligament, single resection of the ischiofemoral or iliofemoral ligament during THA using an anterior or anterolateral approach might not significantly affect axial laxity. At 60° of flexion, movement of the femoral head was relatively large under all conditions with no statistically significant difference. This finding may reflect loosening of the capsular ligaments and a greater contribution of the posterior muscles, such as the gluteus maximus and the hamstrings, to hip stability in this amount of hip flexion.

This study has several limitations. First, although the pubofemoral ligament and lateral band of the iliofemoral ligament contribute to hip stability [3, 22], the function of these ligaments was not evaluated. In this study, we simply simulated THA using the anterolateral approach. When using our standard surgical technique, THA cannot be completed without resection of the lateral arm of the iliofemoral ligament. Moreover, the distal footprint of the pubofemoral ligament merges with the medial arm of the iliofemoral ligament, which meant that we could not selectively evaluate the pubofemoral ligament. A further study is needed to determine the contribution of each capsular ligament to hip stability under various surgical conditions. Second, we did not assess the effect of variation in the size of the femoral head, neck offset, or stem anteversion. van Arkel et al. reported that THA decreased the ability of the native capsular ligaments to restrain hip motion especially when a smaller femoral head was used [1]. The biomechanics of the capsule are also affected by femoral offset, leg length, and femoral neck length. Therefore, the contribution of each element to hip stability could depend on the size of the implant. However, this study focused on the impact of resection or preservation of the capsular ligaments and the conjoined tendon in THA. Nevertheless, the condition of implants ideally should have been standardized in this study. Third, the cadaveric hip specimens used in this study were normal and did not have the thickened and shortened capsular ligaments, bony deformity, and joint contracture typically observed in patients with osteoarthritis of the hip. Thus, our results are not entirely representative of the patients encountered in clinical practice. However, we believe that the normal hip joint was better for evaluation of the true function of the capsule and tendons. Fourth, the sample size was small. Although the number of specimens was validated by a power analysis, the results of the statistical analyses might have been different had the number of specimens been greater. Fifth, the navigation system used in this study does not record movement of the femoral head that is less than 5 mm despite having excellent nominal accuracy of 0.5 mm for translations and 0.5° for rotations [23]. This is because the navigation system recognizes 0–4 mm of movement of the femoral head as normal and displays it as “no lift-off”. This setting is for clinical use, and the normal range (0–4 mm) is defined to reflect the jumping distance (degree of translation of the center of the femoral head required before dislocation occurs) of 28 mm of the prosthetic femoral head after THA. This setting is independent of the accuracy of the navigation system but a characteristic of the product. Therefore, we calculated movement of the femoral head that was less than 5 mm manually using an electronic caliper in the surgical view. We acknowledge that the amount of movement of the femoral head in response to axial traction may vary according to the measurement method used. However, we believe that our protocol was reliable and had minimal effect on our findings given that the measurement order was small and the intraclass correlation coefficients indicated perfect intra-examiner reproducibility (0.99 for range of rotation and 0.98 for amount of movement of the femoral head). Finally, intra-examiner reproducibility was only assessed by the intraclass correlation coefficient. However, we endeavored to reduce error between examinations by fixing the leg in each flexed position using pillows, controlling the rotation torque by a dynamometer, and determining the distraction force by a spring scale. Moreover, the range of hip motion and the amount of movement of the femoral head were monitored in each specimen using a navigation system with a fixed coordinate system. The results obtained by different examiners were essentially the same. Therefore, the intraclass correlation coefficient was adequate for assessing the reproducibility of the results obtained using this examination system.

In conclusion, resection of the iliofemoral ligament during THA markedly increased external rotation of the hip from 10° of extension to 10° of flexion. In contrast, the conjoined tendon and ischiofemoral ligament greatly contributed to internal rotation of the hip. Although the iliofemoral ligament, ischiofemoral ligament, and conjoined tendon each have a minor role in stabilizing the hip when axial traction is applied, resection of two or more of these elements could significantly affect the stability of the joint. Surgeons require an understanding of the effects of resection of the capsular ligaments and the conjoined tendon when performing THA to be able to manage soft tissue appropriately in individual patients.

Acknowledgements:

Not applicable.

Conflict of Interests:

The authors declare that there are no conflict of interests.

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Figure Legends

Fig. 1 (a) Photograph of the anterior aspect of the hip capsule. The black dotted lines show the medial arm of the iliofemoral ligament and the black arrow indicates the resection line of the hip capsule during surgery. (b) Photograph showing the "intact" condition after surgery. The medial band of the iliofemoral ligament and the ischiofemoral ligament are completely preserved. AIIS, anterior inferior iliac spine; ISFL, ischiofemoral ligament; LA, lateral arm of the iliofemoral ligament; MA, medial arm of the iliofemoral ligament

Fig. 2 Photograph showing the positioning of the cadaveric specimen and the CT-based navigation system used in this study. The navigation system can monitor hip motion and alignment with respect to the pelvis dynamically through the infrared sensor camera array by recognizing the motion of the trackers fixed on the femur and pelvis.

Fig. 3 Images captured by the CT-based navigation system. Surface match registration was performed by digitizing more than 30 points on the surfaces of the pelvis and femur.

Fig. 4 Photographs showing the methods used to assess internal rotation of the hip. (a) Assessment of internal rotation in 10° of hip flexion. The left hip was internally rotated by pushing the apex pin inserted into the anterior aspect of the left femur. The force of the push was controlled by a dynamometer and hip alignment was confirmed by the navigation system. Images were captured before (b) and after (c) application of internal rotation torque. The entries bordered by the white square indicate hip alignment.

Fig. 5 Images showing the method used to assess movement of the prosthetic femoral head when distraction force was applied in 10°of hip flexion. (a) Pillows (represented by the hatched areas) were placed between the femur and the surgical table to stabilize the hip in a flexed position. A constant traction force of 250 N was applied using a spring scale through an apex pin inserted into the distal end of the femur. Images were captured before (b) and after (c) traction force was applied. The entries bordered by the white squares indicate hip alignment (the hip position was controlled in neutral during abduction and rotation) and the entry underlined in white indicates the amount of movement of the femoral head.

Fig. 6 Range of external rotation with stepwise resection of the ischiofemoral ligament, the medial arm of the iliofemoral ligament, and the conjoined tendon for each hip flexion angle. Differences were statistically significant at $*P < .05$ or $**P < .01$.

Fig. 7 Range of internal rotation with stepwise resection of the ischiofemoral ligament, the medial arm of the iliofemoral ligament, and the conjoined tendon for each hip flexion angle. Differences were statistically significant at $*P < .05$ or $**P < .01$.

Fig. 8 Amount of movement of the femoral head in response to axial traction with stepwise resection of the ischiofemoral ligament, the medial arm of the iliofemoral ligament, and the conjoined tendon for each hip flexion angle. Differences were statistically significant at $*P < .05$ or $**P < .01$.

Table 1. Range of external rotation after resection of each soft tissue element according to hip flexion angle

	Intact		Ischiofemoral ligament resection			Iliofemoral ligament resection			Conjoined tendon resection		
	Mean (°)	Range	Mean (°)	Range	*P*-value	Mean (°)	Range	*P*-value	Mean (°)	Range	*P*-value
10° of extension	21.9	5–47	25.0	5–52	0.890	40.1	20–60	0.012	45.6	22–66	0.599
Neutral	29.8	13–51	32.1	12–53	0.863	48.5	31–67	< 0.01	49.4	28–70	0.992
10° of flexion	33.1	17–50	36.9	22–52	0.349	45.1	30–61	< 0.01	49.4	30–71	0.248
30° of flexion	39.3	28–48	39.6	27–51	0.993	43.0	30–53	0.116	46.5	38–55	0.098
60° of flexion	38.9	31–52	40.9	33–51	0.524	44.4	35–55	0.104	48.4	37–63	0.053

The *P*-value was calculated for comparison of each ligament before and after resection

Table 2. Range of internal rotation after resection of each soft tissue element according to hip flexion angle

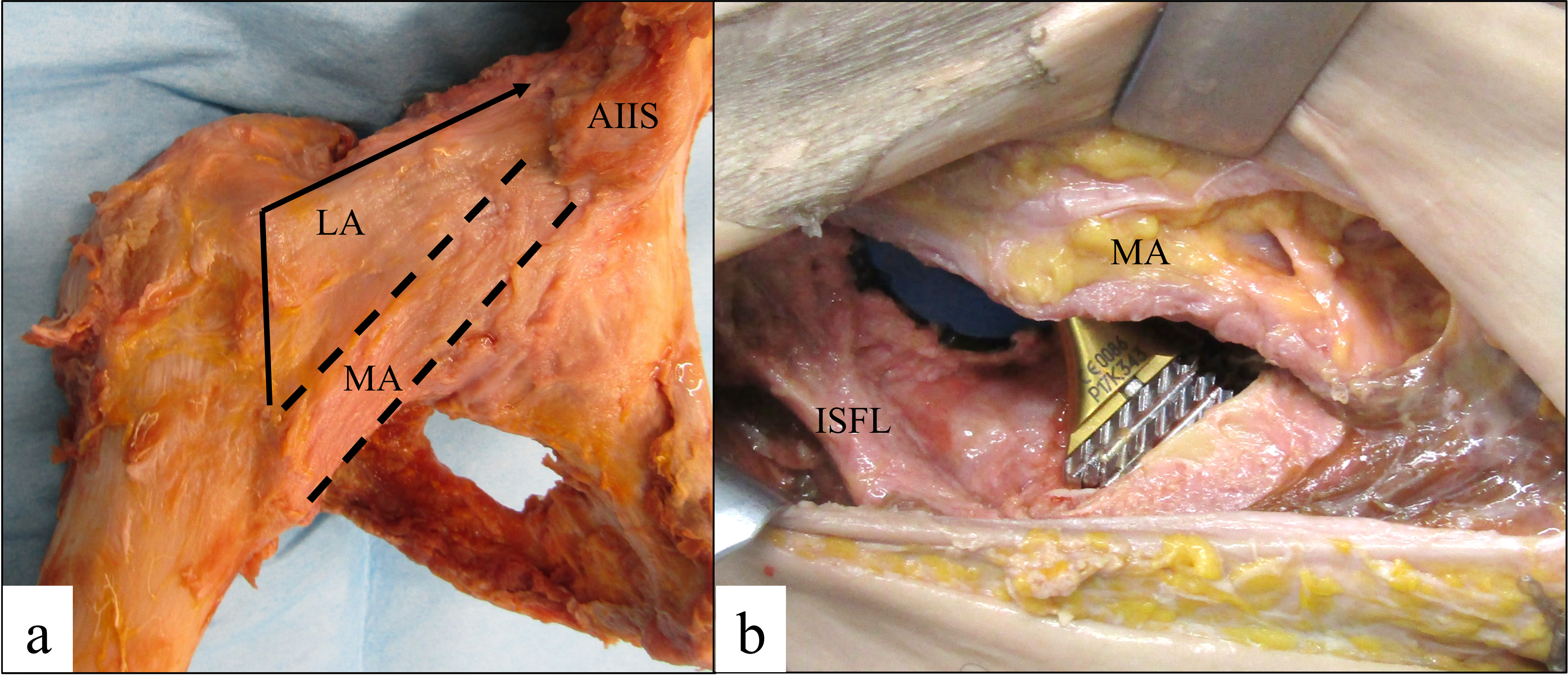
	Intact		Ischiofemoral ligament resection			Iliofemoral ligament resection			Conjoined tendon resection		
	Mean (°)	Range	Mean (°)	Range	*P*-value	Mean (°)	Range	*P*-value	Mean (°)	Range	*P*-value
10° of extension	20.0	12–41	25.4	19–45	0.039	28.1	20–48	0.462	34.1	24–53	0.019
Neutral	23.6	18–44	29.9	19–56	0.366	32.8	22–57	0.869	44.8	29–70	0.021
10° of flexion	24.4	16–46	31.1	23–53	0.386	35.0	25–61	0.787	48.0	27–72	0.024
30° of flexion	24.3	14–45	31.9	23–59	0.243	35.1	26–62	0.842	47.4	26–70	0.025
60° of flexion	27.3	16–53	32.8	18–56	0.377	37.4	25–57	0.524	41.8	29–64	0.569

The *P*-value was calculated for comparison of each ligament before and after resection

Table 3. Amount of movement of the center of the femoral head when axial traction was applied according to hip flexion angle

	Intact		Ischiofemoral ligament resection			Iliofemoral ligament resection			Conjoined tendon resection		
	Mean (mm)	Range	Mean (mm)	Range	*P*-value	Mean (mm)	Range	*P*-value	Mean (mm)	Range	*P*-value
10° of extension	2.8	0–8	3.9	0–11	0.487	6.0	0–13	0.056	6.8	0–16	0.771
Neutral	4.5	0–11	6.4	0–11	0.299	9.1	4–13	0.067	10.6	2–18	0.487
10° of flexion	7.3	0–13	9.5	1–14	0.202	11.1	4–17	0.466	14.1	6–19	0.056
30° of flexion	10.6	2–17	11.6	4–17	0.803	15.5	7–21	0.011	15.3	7–19	0.996
60° of flexion	12.4	4–19	14.5	8–21	0.655	17.4	7–26	0.413	17.3	6–23	1.000

The *P*-value was calculated for comparison of each ligament before and after resection.


AIIS
LA
MA
a
MA
ISFL
b

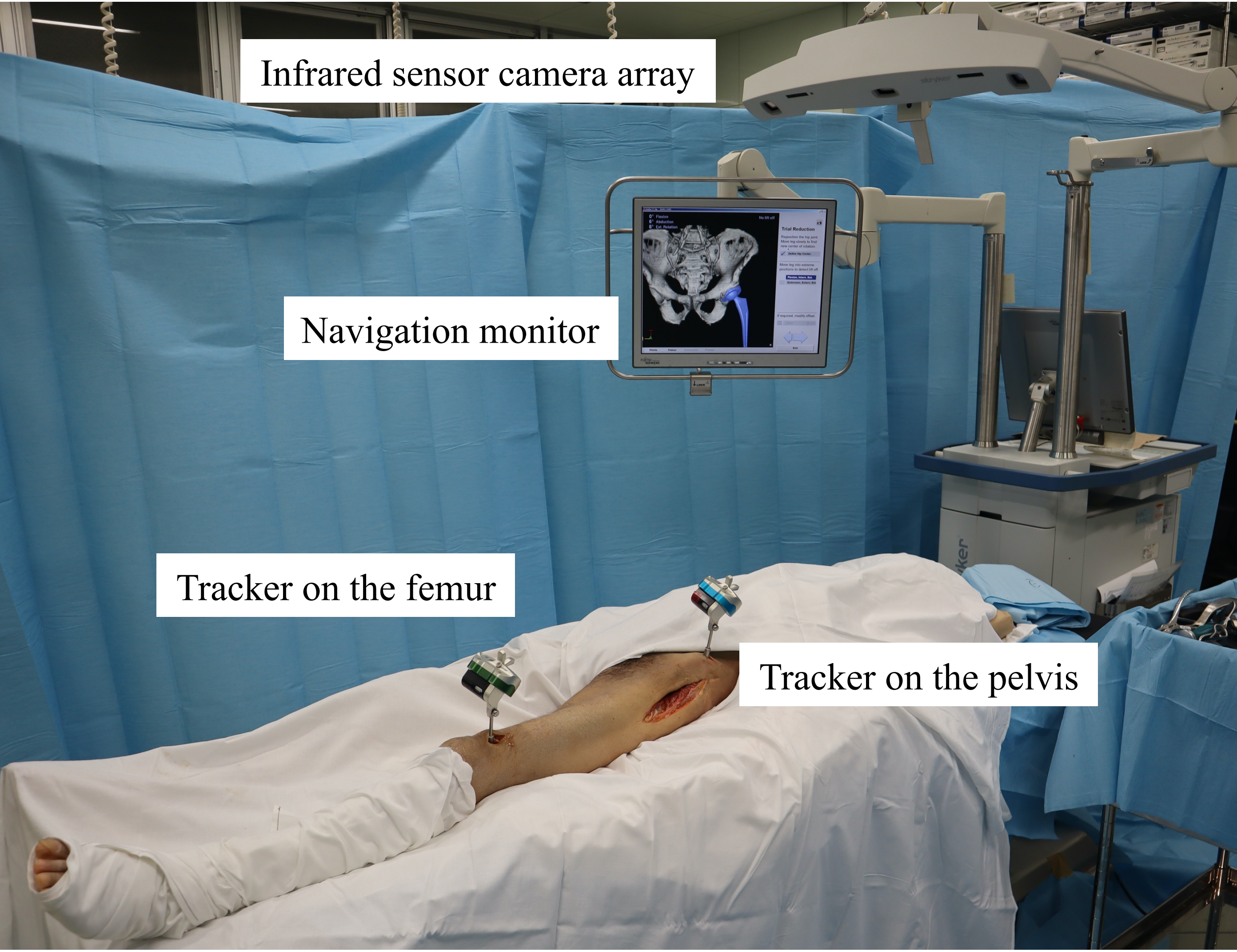

Infrared sensor camera array
Navigation monitor
Tracker on the femur
Tracker on the pelvis

Fig.2

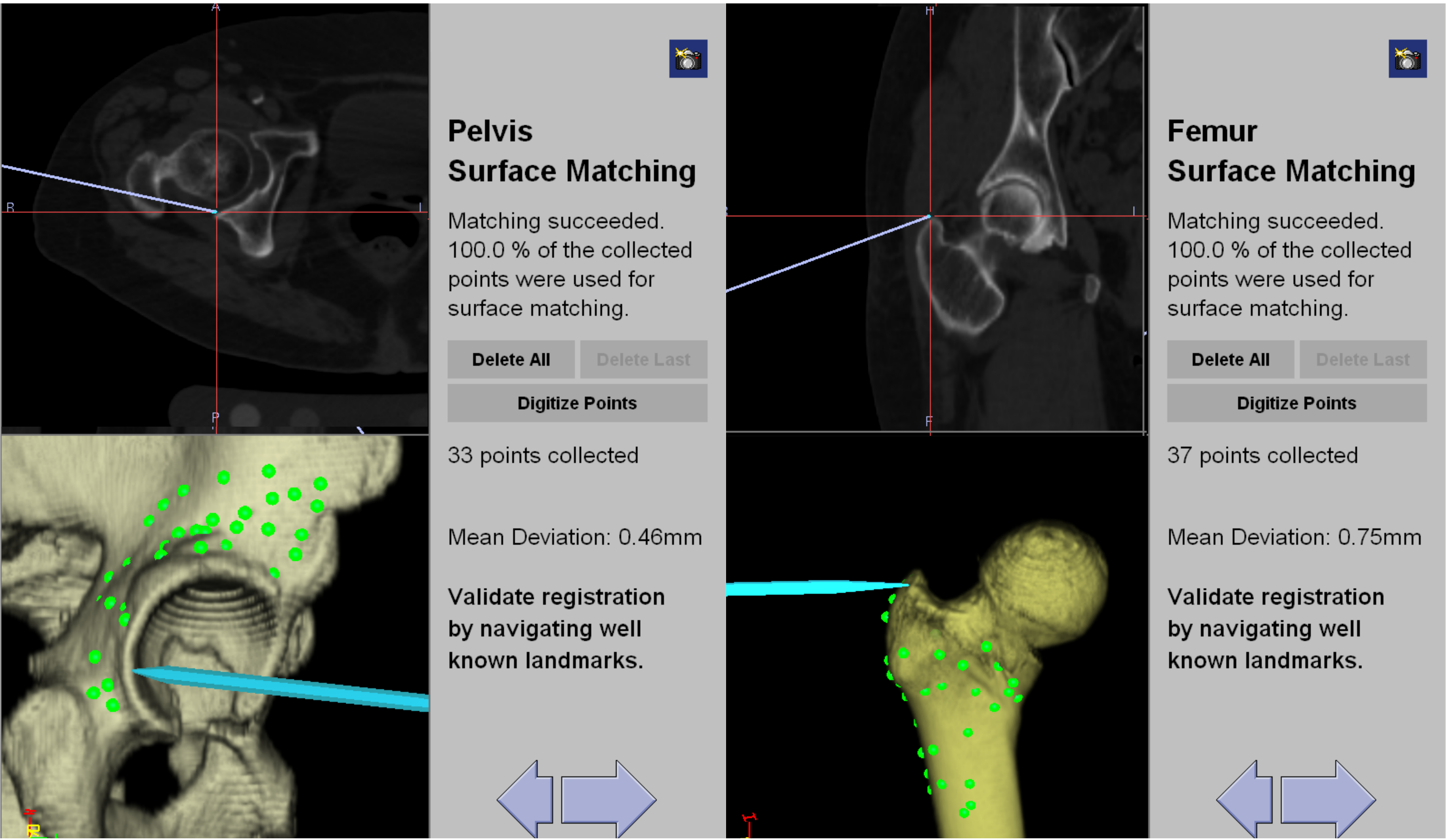

Pelvis
Surface Matching
Matching succeeded.
100.0 % of the collected points were used for surface matching.
Delete All
Delete Last
Digitize Points
33 points collected
Mean Deviation: 0.46mm
Validate registration by navigating well known landmarks.
Femur
Surface Matching
Matching succeeded.
100.0 % of the collected points were used for surface matching.
Delete All
Delete Last
Digitize Points
37 points collected
Mean Deviation: 0.75mm
Validate registration by navigating well known landmarks.

Fig.3

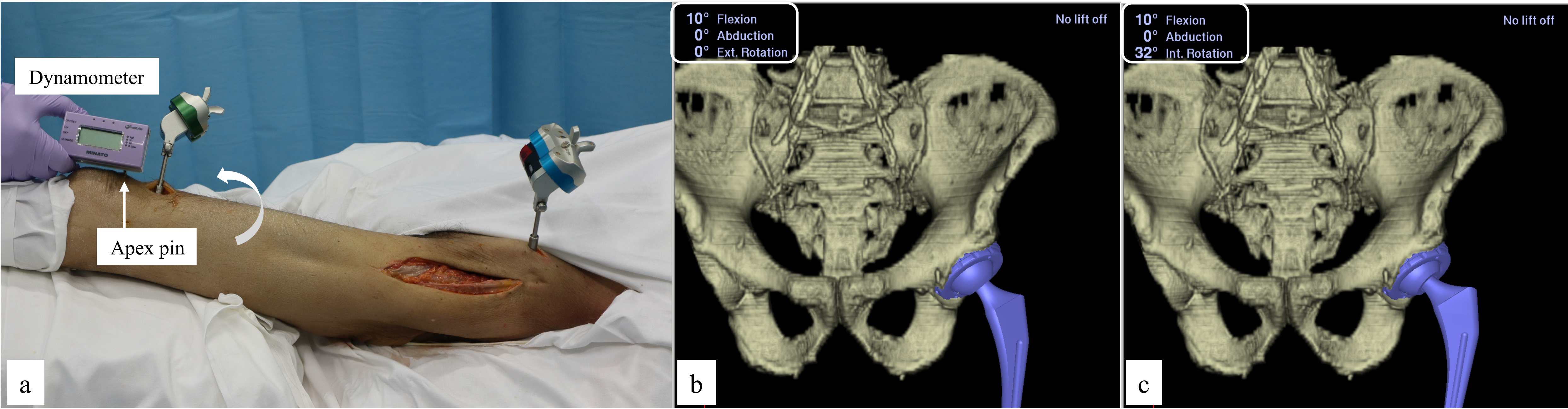

Dynamometer
Apex pin
a
10° Flexion
0° Abduction
0° Ext. Rotation
No lift off
b
10° Flexion
0° Abduction
32° Int. Rotation
No lift off
c

Fig.4

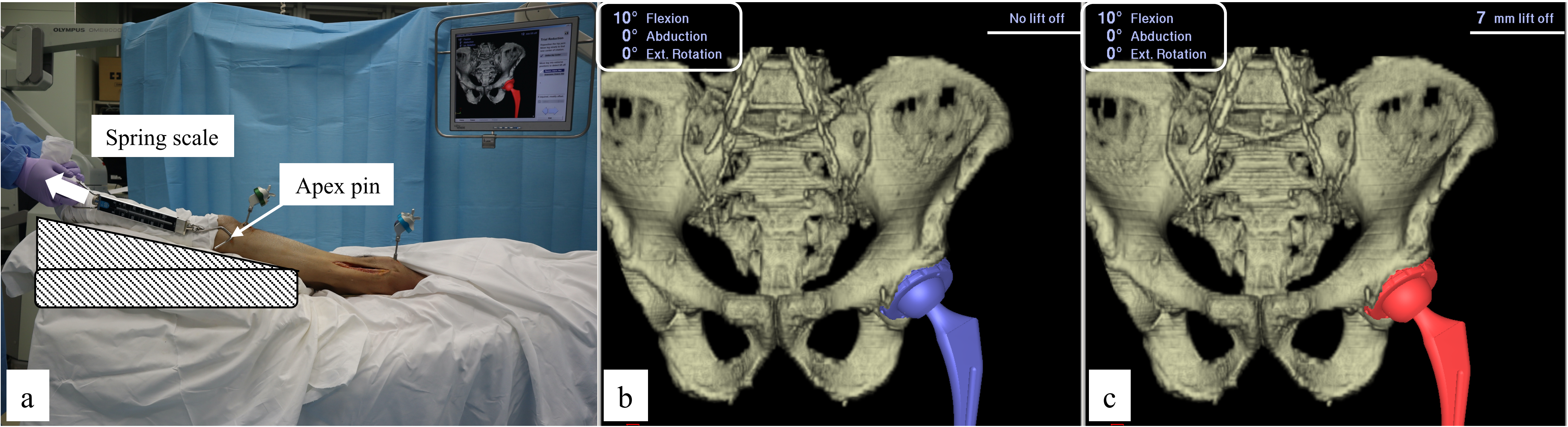

Spring scale
Apex pin
a
10° Flexion
0° Abduction
0° Ext. Rotation
No lift off
b
10° Flexion
0° Abduction
0° Ext. Rotation
7 mm lift off
c

Fig.5

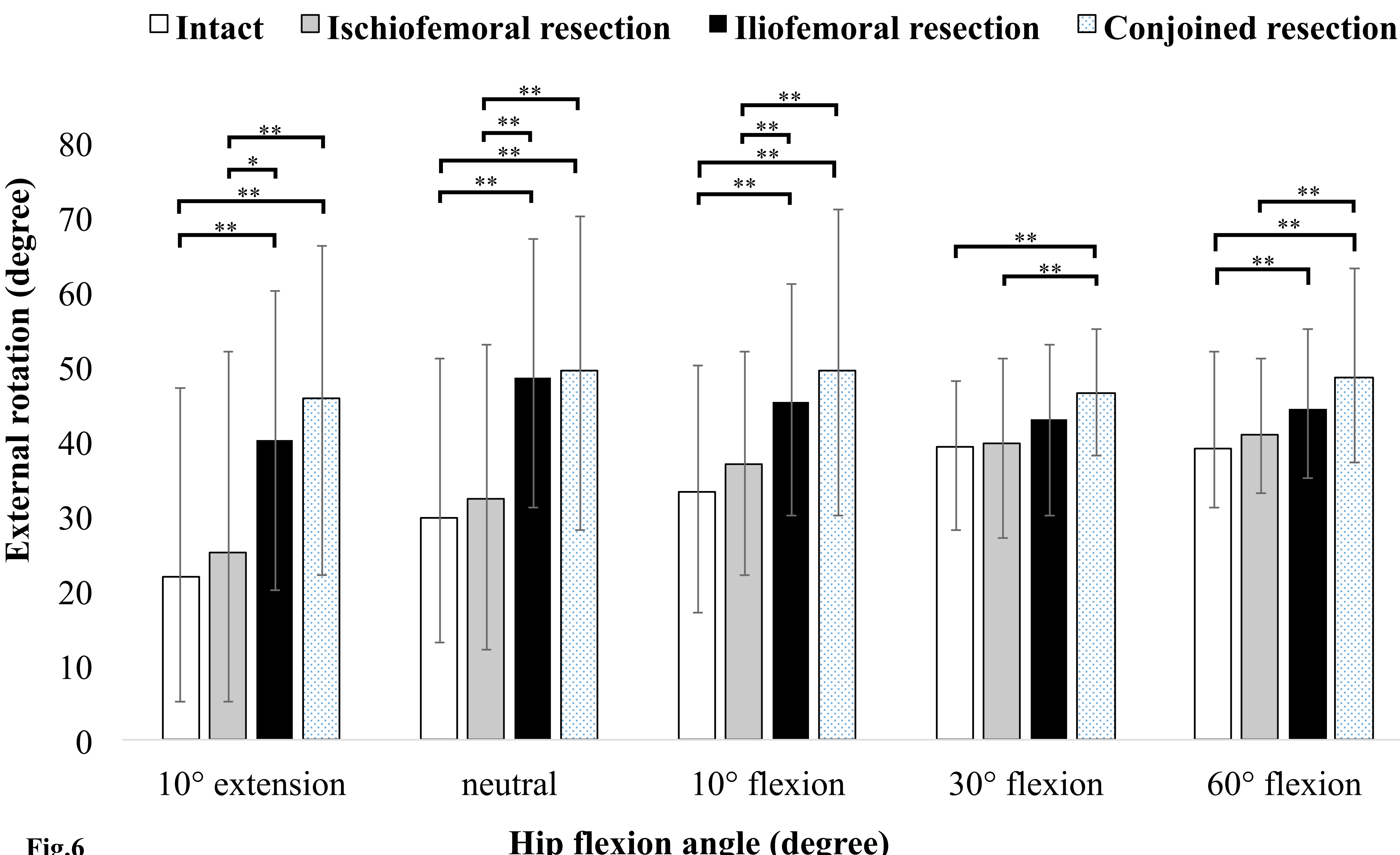
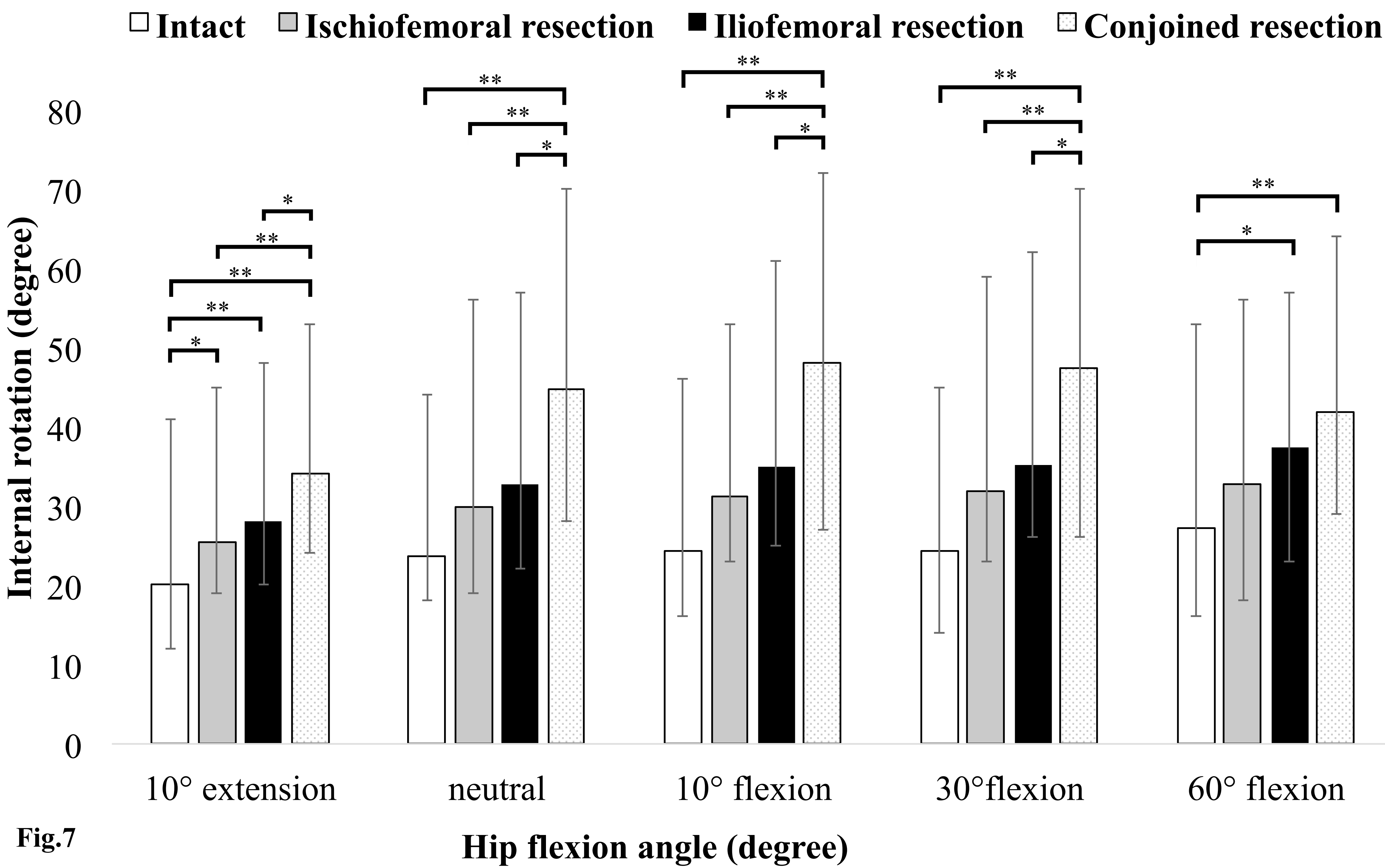
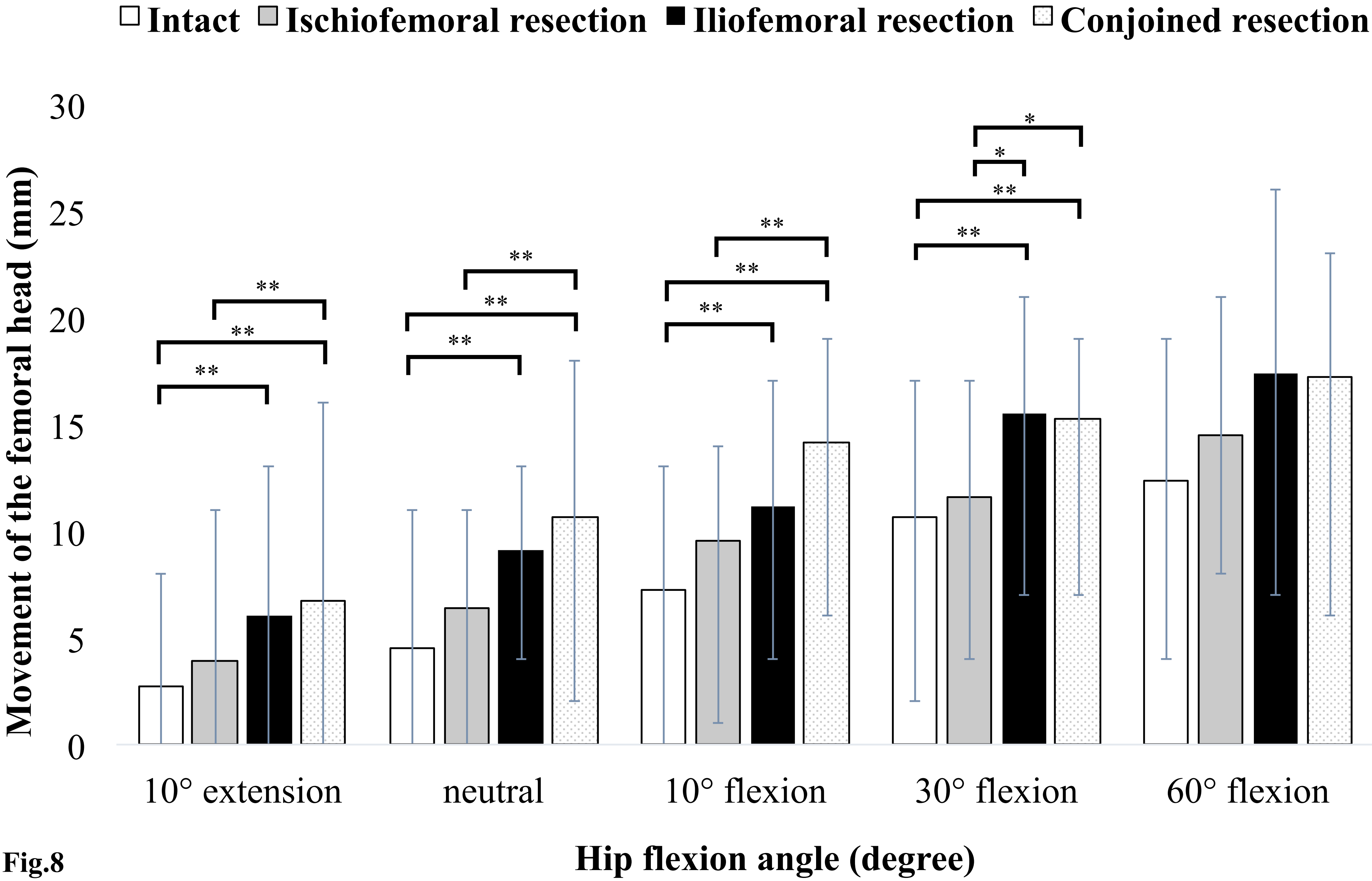

Intact
Ischiofemoral resection
Iliofemoral resection
Conjoined resection
External rotation (degree)
0
10
20
30
40
50
60
70
80
**
*
10° extension
neutral
10° flexion
30° flexion
60° flexion
Hip flexion angle (degree)

Fig.6



Intact
Ischiofemoral resection
Iliofemoral resection
Conjoined resection
Internal rotation (degree)
0
10
20
30
40
50
60
70
80
*
**
10° extension
neutral
10° flexion
30°flexion
60° flexion
Hip flexion angle (degree)

Fig.7



Intact
Ischiofemoral resection
Iliofemoral resection
Conjoined resection
Movement of the femoral head (mm)
30
25
20
15
10
5
0
**
*
10° extension
neutral
10° flexion
30° flexion
60° flexion
Hip flexion angle (degree)

Fig.8