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ORIGINAL PAPER

Safety range for acute limb lengthening in primary total hip arthroplasty

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Abstract

Purpose There is no documented maximum amount that an extremity can be safely lengthened in primary total hip arthroplasty (THA) without neurologic or soft tissue complications. We retrospectively reviewed patients who underwent primary THA with acute limb lengthening and investigated the safety range for acute limb lengthening in primary THA.

Methods This study included 61 hips in 52 patients who underwent primary THA with acute limb lengthening (more than 2.5 cm) without femoral shortening osteotomy. The amount of lengthening was measured from pre-operative and post-operative X-ray films using computer graphics software, then the ratios of the amount of lengthening to femoral length (L/F ratio = amount of lengthening / femoral shaft length × 100) were calculated. We investigated correlation with nerve and soft tissue complications at operation in regard to this index.

Results The average amount of lengthening was 3.0 cm (2.5 to 4.8). The average L/F ratio was 7.9 (6.2 to 12.9). There were seven nerve complications and two soft tissue complications in the whole series. In all nine complications, eight indicated higher L/F ratios than 8.7. Altogether, 12 hips indicated a higher L/F ratio than 8.7; 66% of them showed neurological or soft tissue problems. ROC curve analysis indicated that the optimal cutoff value of the L/F ratio was 8.7, which predicted acute lengthening-related complications with a sensitivity of 88.9% and a specificity of 92.3% (AUC = 0.88).

Conclusion The patients who underwent THA with acute lengthening of more than 8.7% of femoral shaft length are at high risk of complications caused by acute limb lengthening in primary THA.

Keywords Complication · Limb lengthening · Nerve injury · Primary total hip arthroplasty · Soft tissue contracture

Introduction

Lengthening of shortened leg for leg-length equalization is sometimes required in primary total hip arthroplasty (THA) for developmental dysplasia of the hip (DDH) or advanced osteoarthritis. Appropriate correction of leg-length discrepancy is an essential procedure in primary THA. In some cases, however, leg lengthening gives rise to complications such as nerve palsy, contracture, soft tissue trouble, and leg-length inequality.

Nerve injury is one of the most serious complications in THA [1–6], one which particularly influences post-operative limb function and patient satisfaction. When nerves are pulled excessively and acutely, the axonal flow is affected, which can result in nerve injuries such as neurapraxia or axonotmesis. Excessive leg lengthening in primary THA may cause such changes.

Soft tissue problems, such as flexion or abduction contracture, skin troubles, and so on, also can result from hyperlengthening.

Though we know that acute limb lengthening carries the risk of such serious consequences, there is no documented maximum amount that an extremity can be safely lengthened in primary THA without neurologic or soft tissue complications. In this study, we retrospectively reviewed patients who had undergone primary THA with acute limb lengthening and investigated the safety range for acute limb lengthening in primary THA.

Materials and methods

This study was retrospective. Between April 2004 and March 2016, all 662 patients undergoing 821 primary THAs

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(cementless or hybrid) performed at our institute. This study included 61 hips in 52 patients who underwent primary THA with acute limb lengthening (more than 2.5 cm) without femoral shortening osteotomy. There were seven men and 45 women, with a mean age of 61 years (39 to 81) at operation. The mean follow-up period of 61 joints was five years and four months (range 20 months to12 years), with no lost follow-ups within 20 months. Pre-operative diagnoses included DDH in 53 hips (Crowe group 3, group 4, coxa plana with high-riding greater trochanter, etc.) and others in eight hips (infection, trauma, congenital disease, etc.). Six of the eight cases with non-DDH-related osteoarthritis had developmental leg-length discrepancies with onsets in childhood or early adolescence. The remaining two cases were adult onset severe protrusio acetabuli due to rheumatoid arthritis or radiation, which had gradually developed a leg-length discrepancy over more than ten years. All of the studied hips had rigid joint conditions. All frail hips, such as intramuscular dislocated hips, were excluded from this study. Sixteen cases had several surgical interventions during the growth period or in childhood: pelvic osteotomy in three, proximal femoral osteotomy in six, open reduction of the hip in one, open drainage in one, arthrodesis in one, and unknown procedures in seven. There were no neurovascular problems which required pre-operative clinical intervention.

All surgery was performed by a single surgeon (TK) using a posterior approach in a lateral decubitus position under general anaesthesia. All acetabular components in this study group were cementless press-fit titanium shells. Several different types of femoral stems were used in this study because each stem was selected during pre-operative planning using a 3D-template. Pre-operative planning to determine the optimal component size and position, the amount of leg lengthening, and the amount of offset was performed using both manual radiographic templating and 3D-templating. Basically, we aimed for the same leg length on the affected side and the contralateral side, and the same post-operative global femoral offset (GFO) as the preoperative GFO. In some cases with a narrow femoral canal, we could not use a stem with the required offset length, so leg-length equalization was given preference over offset reconstruction. When more than 4 cm lengthening is indicated in pre-operative planning, we usually perform femoral shortening osteotomy. Such cases were excluded in this study. During surgery, we did not expose the sciatic nerve, did not assess nerve tension, and did not perform neurolysis. Circumferential capsular release was performed in all cases. After the cup was placed in the planned position and femoral canal preparation was completed, a trial reposition with a smaller trial stem than the planned size was performed. After the trial reposition, we checked soft tissue tension around the joint and selectively released tight parts of the soft tissue. If the major muscles around the hip, such as the iliopsoas tendon or rectus femoris, were too tight, we performed a partial release or a needle piecrust procedure to loosen them. After that, a second trial reposition using the planned size trial stem was performed. We routinely obtained intra-operative radiographs after insertion of the acetabular cup, trial liner, trial femoral stem, and trial femoral head with repositioning in order to check the implant position, alignment, leg length, and offset [7]. If something did not correspond to the pre-operative planning, the surgeon made intra-operative adjustments to change it.

Patient evaluations (especially of neurological evaluations and soft tissue conditions) were carried out before and after surgery and at final follow-up. Soft tissue conditions such as contractures were evaluated by both physical examinations and image analysis (X-ray and CT). Soft tissue conditions and neurological findings were evaluated by at least two physicians, the main surgeon (TK) and at least one assistant physician.

The amount of lengthening and the change in GFO were measured from pre-operative and post-operative digital X-ray films using computer graphics software (Picture archiving and communications system, EV Insite net/EV InsiteR R ver.3.1.1.218; PSP corporation, Tokyo, Japan), and the ratio of the amount of lengthening to femoral length (L/F ratio = amount of lengthening / femoral shaft length × 100) was calculated. All the distances shown by computer graphics software were compensated using a calibration measure or the femoral head diameter. The data for all patients were measured twice, at least two weeks apart, by one surgeon (TK). The mean of the two measured values was used in the analysis. The inter-class correlation coefficient was 0.922.

Assessing the amount of lengthening

In brief, pre-operative and post-operative anteroposterior radiographs of the pelvis in the supine position were used to assess the amount of lengthening. Among the several available pre-operative or post-operative radiographs, the almost perfectly well-taken ones (no abduction or adduction of the femur) were chosen for the measurement. First, the trans-teardrop lines were drawn. Second, several bilateral anatomically useful landmarks, such as the apex of the lesser trochanter, the apex of the greater trochanter, the most lateral point of the greater trochanter, the point of characteristic spur formation, and so on, were marked in both the pre- and post-operative radiographs. After that, the parallel lines of the trans-teardrop line were drawn through the respective anatomical landmarks (Fig. 1a, b). Pre-operative leg-length discrepancy, post-operative leg-length discrepancy, and the amount of lengthening were calculated using the distance between the trans-teardrop line and several parallel lines (Fig. 1c).

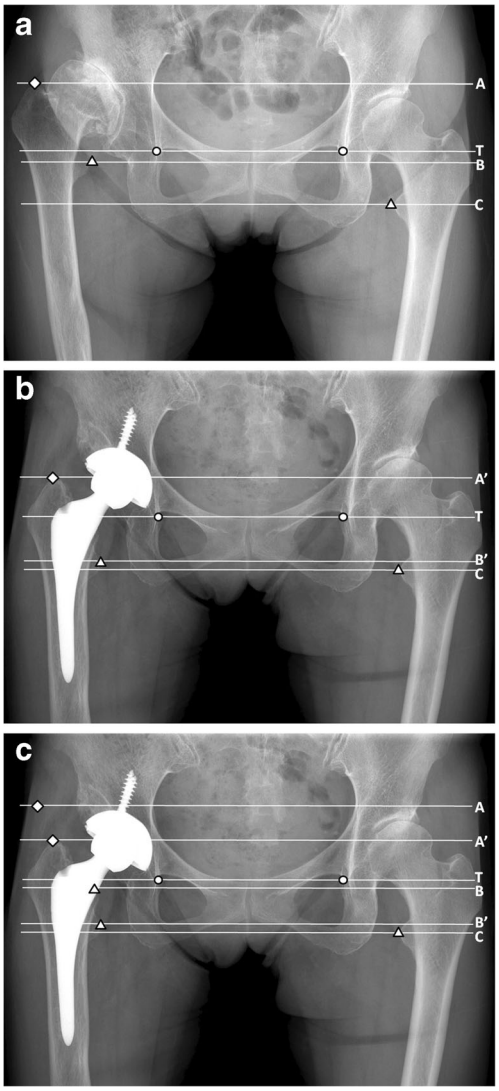

Fig. 1 **a** Pre-operative anteroposterior radiographs of the pelvis in the supine position. T: trans-teardrop line; A: parallel line of the trans-teardrop line through the apex of the greater trochanter. B: parallel line of the trans-teardrop line through the rt. apex of the lesser trochanter. C: parallel line of the trans-teardrop line through the lt. apex of the lesser trochanter. ○: apex of the teardrop; △: apex of the lesser trochanter; ◇: apex of the greater trochanter. The pre-operative leg-length discrepancy was defined as the distance between B and C. **b** Post-operative anteroposterior radiographs of the pelvis in the supine position. A': parallel line of the trans-teardrop line through the post-operative rt. apex of the greater trochanter. B': parallel line of the trans-teardrop line through the post-operative rt. apex of the lesser trochanter. The post-operative leg-length discrepancy was defined as the distance between B' and C. **c** The amount of lengthening was defined as the distance between A and A' or B and B'. The better-marked anatomical landmark (A or B) was chosen for measurement

Measuring the femoral length

Femoral length was defined as the distance between the proximal and distal end points of the femoral shaft. The proximal end of the femoral shaft was defined as the intersecting point of the anatomical axis of the femur and its perpendicular line through the apex of the greater trochanter. The distal end of the femoral shaft was defined as the intersection of the anatomical axis of the femur and the distal femoral joint line (Fig. 2).

Measuring the global femoral offset (GFO)

GFO was measured by adding the distance between the longitudinal axis of the femur and the center of the femoral head to the distance between the centre of the femoral head and a perpendicular line passing through the pubic symphysis (Fig. 3). The measurement was performed both pre-operatively and post-operatively. The amount of change in GFO was defined by subtracting the pre-operative GFO from the post-operative GFO. Thus, a positive value was obtained when the post-operative GFO was greater than the pre-operative, while a negative value indicated the opposite.

We investigated the correlation of nerve and soft tissue complications at operation with regard to the L/F ratio index. The cutoff values of the L/F ratio were determined by the receiver-operating characteristic (ROC) curve analysis. All statistical analyses were performed using a statistical software package (SPSS software for Windows, version 23.0; SPSS, Inc., Chicago, IL). Group comparisons were performed for quantitative data using the Mann–Whitney *U* tests and Student's *t* test, for categorical data using the Fisher's exact test.

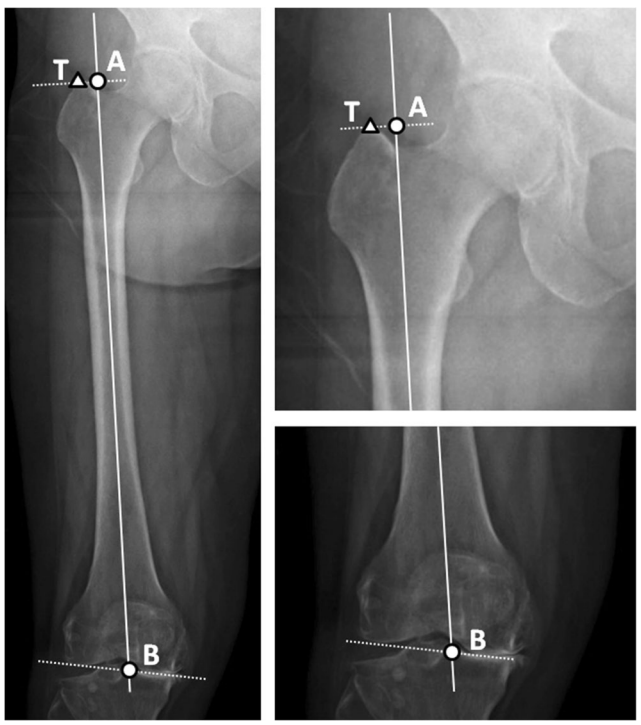

Fig. 2 A: Proximal end of the femoral shaft. B: Distal end of the femoral shaft. T: Apex of the greater trochanter. Femoral length was defined as the distance between A and B

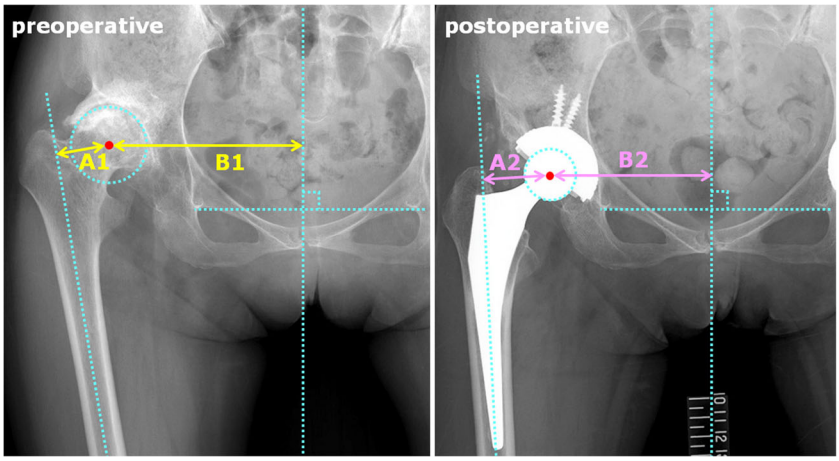

Fig. 3 Measurement of grovel femoral offset (GFO). The pre-operative global femoral offset was measured by adding the distance between the longitudinal axis of the femur and the centre of the femoral head (A1) to the distance between the centre of the femoral head and a perpendicular line passing through the pubic symphysis (B1). The post-operative GFO was measured by adding A2 and B2 in a similar manner. The change in GFO was defined by subtracting pre-operative GFO from post-operative GFO ((A2 + B2) − (A1 + B1))

This investigational protocol was conducted with the approval of the Kanazawa University Graduate School of Medical Science Ethics Committee. All subjects were provided informed consent. The authors declare that they have no conflict of interest. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Results

The average amount of lengthening was 3.0 cm (2.5 to 4.8). The average L/F ratio was 7.9 (6.2 to 12.9). The average amount of change in GFO was − 4.1 mm (− 44.2 to 24.7) (Table 1).

There were seven nerve complications in the whole series; two showed a partial motor deficit, and five showed a temporary sensory disturbance. Both motor deficits experienced a complete recovery, and all sensory disturbances had almost normalized within two years. In addition, there were two severe flexion contractures which were salvaged by additional soft tissue release (Table 1). We define a severe flexion contracture as a situation in which the patient cannot lie on his or her stomach. There were no neurological complications or severe soft tissue complications in the patients excluded from this study (those whose legs were lengthened within 2.5 cm).

The average amount of lengthening in patients with complication was 3.6 cm (2.7 to 4.8); in patients without complications it was 2.9 cm (2.5 to 4.2). The average L/F ratio in patients with complications was 9.9 (6.6 to 12.9); in patients without complications it was 7.6 (6.2 to 12.6). Both the average amount of lengthening and the average L/F ratio were significantly higher in patients with complications than in those without. The average amount of change in GFO in patients with complications was − 6.8 mm (− 44.2 to 4.5); in those without complications it was − 3.6 mm (− 21.9 to 24.7). No significant difference was found between patients with and without complications (Table 2). Focusing on motor deficit (Tables 3, 4, and 5), there was no statistically significant difference in L/F ratio and GFO change between two cases with partial motor deficit and five cases with temporary sensory disturbance without motor deficit (Table 3). In the same way, there was no statistically significant difference between two cases with partial motor deficit and seven cases with complications without motor deficit (Table 4). We could only note that the L/F ratio was significantly higher in the two cases with motor deficit than in the 59 cases without motor deficit (Table 5).

In all nine complications, eight had indicated L/F ratios higher than 8.7. Only one neurological problem (numbness along the dorsum of foot) developed in a hip with an L/F ratio lower than 8.7. Altogether, 12 hips indicated a higher L/F ratio than 8.7; 66% of them showed neurological or soft tissue problems. No clear association could be found between the amount of change in GFO and the occurrence of complications.

ROC curve analysis indicated that when the cutoff value of L/F ratio was set at 8.7, the sensitivity was 88.9% and the specificity was 92.3% (AUC = 0.88, Fig. 4).

Case series

Case 1: 66-year-old male—bilateral Crowe group 4 dislocated hip (Fig. 5a, b)

He had partial peroneal nerve palsy, from which he recovered conservatively 2 years after surgery. Amount of lengthening, 3.54 cm; femoral shaft length, 36.1 cm; L/F ratio = 9.8.

Table 1 Summary of all patient's data

Patients	Age	Sex	Diagnosis	Amount of LL (cm)	Height (cm)	Length of femur (cm)	L/F ratio	Change of GFO (mm)	Complication
1. KF	39	Female	DDH	2.7	167	40.7	6.6	4.5	Sensory disturbance
2. NM	56	Male	DDH	3.7	161	39.4	10.4	− 6.7	Sensory disturbance
3. KB	50	Female	DDH	3.4	156	38.5	8.9	− 3.5	Sensory disturbance
4. KB	50	Female	DDH	2.7	156	38.5	7.0	− 13	
5. HA	58	Male	Irradiated hip	2.5	159	38.0	6.6	24.7	
6. TB	73	Female	Post-infection	2.9	151	36.3	8.1	0	
7. MM	51	Female	DDH	3.5	155	38.0	9.1	− 44.2	Sensory disturbance
8. CA	50	Female	Morquio disease	2.9	130	32.2	9.0	− 6.9	
9. SM	73	Male	Post infection	3.0	163	39.0	7.6	5.3	
10. MT	58	Female	DDH	2.5	143	34.2	7.3	− 8.7	
11. YS	49	Female	DDH	2.9	158	38.9	7.5	− 6.1	
12. KA	50	Female	DDH	2.8	163	39.3	7.2	− 21.9	
13. MS	47	Female	RA	2.5	145	34.5	7.2	− 4.2	
14. MO	71	Female	DDH	2.7	148	36.7	7.4	1.8	
15. CA	51	Female	Morquio disease	3.7	130	32.2	11.3	− 8.7	Sciatic nerve palsy
16. MO	71	Female	DDH	2.7	148	36.7	7.4	− 7.0	
17. MS	47	Female	DDH	2.5	156	38.2	6.6	− 8.0	
18. KT	55	Female	DDH	3.0	141	36.5	8.3	− 0.9	
19. ST	58	Male	Perthes disease	2.9	169	43.1	6.7	4.5	
20. HA	64	Female	DDH	2.8	146	34.5	8.2	− 4.4	
21. YM	77	Female	DDH	4.2	140	33.3	12.6	− 7.1	
22. KN	68	Female	DDH	2.5	145	36.4	6.9	− 2.6	
23. NN	60	Female	DDH	3.0	154	37.5	8.0	− 16.7	
24. KM	72	Female	DDH	2.9	152	38.5	7.5	− 6.2	
25. KM	81	Female	DDH	2.6	151	36.7	7.0	0.9	
26. KT	57	Female	DDH	3.4	155	39.6	8.5	− 2.6	
27. TN	66	Male	DDH	3.5	144	36.1	9.8	− 7.9	Peroneal nerve palsy
28. KT	57	Female	DDH	2.9	155	39.6	7.4	3.5	
29. KY	81	Female	DDH	3.0	156	41.5	7.2	8.5	
30. KI	70	Female	DDH	4.8	151	37.4	12.9	− 0.9	Sensory disturbance
31. TM	72	Female	DDH	2.7	138	36.0	7.5	7.2	
32. MG	66	Female	DDH	3.0	157	40.1	7.5	− 1.8	
33. TM	73	Female	DDH	2.7	138	36.0	7.5	− 2.7	
34. SK	63	Female	DDH	2.5	143	38.9	6.5	− 19.0	
35. SN	50	Female	DDH	2.4	153	37.9	6.5	− 19.1	
36. AH	73	Female	DDH	3.6	142	35.6	10.2	3.2	Severe contracture
37. YY	73	Female	DDH	2.5	153	39.4	6.4	− 2.0	
38. AH	73	Female	DDH	3.6	142	35.8	10.2	3.2	Severe contracture
39. KM	72	Female	DDH	3.1	148	37.3	8.2	− 16.4	
40. TI	64	Female	DDH	3.1	147	37.5	8.3	0	
41. CT	67	Female	DDH	3.4	151	40.1	8.5	− 13.8	
42. TS	79	Female	DDH	3.5	145	38.0	9.3	− 7.6	
43. KM	64	Female	DDH	2.8	151	36.8	7.6	− 16.7	
44. KM	64	Female	DDH	2.9	151	36.8	7.9	− 4.2	
45. KF	56	Female	DDH	2.8	142	33.9	8.3	− 3.4	
46. TA	53	Male	DDH	3.2	174	42.9	7.6	− 15.9	
47. TK	63	Female	DDH	2.7	146	35.9	7.6	− 12.3	
48. SI	55	Female	DDH	2.7	152	37.9	8.0	− 2.1	

Table 1 (continued)

Patients	Age	Sex	Diagnosis	Amount of LL (cm)	Height (cm)	Length of femur (cm)	L/F ratio	Change of GFO (mm)	Complication
49. YK	62	Female	DDH	2.8	144	37.4	7.5	− 4.9	
50. TK	61	Female	DDH	2.6	152	37.9	7.0	− 5.8	
51. YA	62	Female	DDH	2.5	138	34.4	7.3	5.7	
52. TK	67	Female	DDH	2.5	154	40.3	6.2	9.8	
53. SI	51	Female	DDH	2.6	157	40.3	6.3	− 2.2	
54. YA	70	Male	Post-trauma	2.5	164	40.3	6.3	7.1	
55. HT	62	Female	DDH	2.9	151	38.8	7.4	1.5	
56. JM	59	Female	DDH	3.0	154	35.5	8.5	− 3.6	
57. KT	62	Female	DDH	3.7	146	38.1	9.7	10.6	
58. KT	62	Female	DDH	2.5	146	37.1	6.8	− 3.7	
59. FF	64	Female	DDH	3.1	146	36.4	8.6	− 2.3	
60. YY	46	Female	DDH	2.9	162	40.7	7.1	− 3.4	
61. YY	46	Female	DDH	2.5	162	40.3	6.2	0.1	
Average	61			3.0	150	37.6	7.9	− 4.1	

DDH developmental dysplasia of the hip
RA rheumatoid arthritis
LL leg lengthening
GFO global femoral offset

Case 2: 53-year-old male—left Crowe group 2 hip (Fig. 6a, b)

He had no nerve symptoms or soft tissue problems after surgery, even though his amount of lengthening was 3.7 cm. Because he was a tall man, his femoral shaft length was 48.5 cm, so the L/F ratio became less than 8.7. Amount of lengthening, 3.7 cm; femoral shaft length, 48.5 cm; L/F ratio = 7.6.

Discussion

There have been a number of reports about the safety range for acute limb lengthening in primary THA. Edwards et al. considered leg lengthening to be a significant risk factor, finding that a mean lengthening of just 2.7 cm may damage the peroneal part of the sciatic nerve, while 4.4 cm may put the entire sciatic nerve at risk [1]. Schmalzried et al. reported on six patients in whom elongation of more than 3 cm caused nerve injury [2]. Johanson et al. reported that the rate of neurologic injury was 28% in those who had an acute lengthening of more than 4 cm while no patient who had a lengthening of less than 4 cm developed a nerve palsy [3]. Meanwhile, Dunn et al. reported that 5 to 7 cm lengthening could be performed safely for chronically dislocated hips [4]. Most of the clinical reports which showed safety ranges for acute limb lengthening were based on the authors' clinical experience, not scientific theory. Meanwhile, several reports have concluded that nerve injury after THA has no strong association with the amount of lengthening [2, 5, 6]. To our knowledge, there is

Table 2 Comparison of the patients with and without complications

	Patients with complications ($n = 9$)	Patients without complications ($n = 52$)	P value
Sex	male:female = 2:7	male:female = 5:47	0.27
Diagnosis	DDH:Others = 8:1	DDH:Others = 44:8	0.99
Mean age	54.6 + 9.7	61.6 + 9.9	0.14
Mean head diameter (mm)	25.8 + 2.2	26.8 + 2.6	0.21
Mean height (cm)	147.1 + 9.9	150.8 + 8.4	0.17
Mean length of femur (cm)	37.0 + 2.5	37.7 + 2.3	0.82
Mean amount of LL (cm)	3.6 + 0.5	2.9 + 0.3	0.0002
Mean L/F ratio	9.9 + 1.6	7.6 + 1.1	0.0003
Mean change of GFO (mm)	− 6.8 + 14.1	− 3.6 + 8.6	0.88

DDH developmental dysplasia of the hip
GFO global femoral offset

Table 3 Comparison of patients with motor deficit and with sensory disturbance without motor deficit

	Patients with motor deficit ($n = 2$)	Patients with sensory disturbance without motor deficit ($n = 5$)	P value
Mean L/F ratio	10.5 + 1.1	9.6 + 2.3	0.61
Mean change of GFO (mm)	− 8.3 + 0.6	− 10.1 + 19.5	0.25

GFO global femoral offset

no general consensus about the relationship between nerve injury after primary THA and the amount of lengthening, and there is no documented maximum amount that an extremity can be safely lengthened without neurologic complications. As for soft tissue problems, it is widely known that excessive acute lengthening carries the risk of creating soft tissue troubles. But there are no detailed reports about its incidence, risk factors, and safety range.

In basic research, several animal experimental studies addressed the safety range of acute nerve lengthening. Tanoue et al. reported that 11% nerve strain (same as 20% femoral lengthening) caused severe nerve damage, but 6% strain (same as 10% femoral lengthening) caused no damage [8]. Sunderland et al. reported that nerve elongation of more than 6% was associated with neural injury [9]. Considering these experimental data, the risk of nerve damage should become theoretically higher as the amount of lengthening becomes greater, and the safe amount of lengthening should be determined for every individual physique.

We considered that the upper limitation on the amount of lengthening should be determined according to each individual patient's physique. Therefore, we selected the length of the femur, which can be measured with ease, as a reference index for the amount of limb lengthening. Aging has little effect on the length of long bones such as the femur, making them appropriate as an index which reflects each patient's physique or nerve length.

There was a report in which the length of the femur was adopted as a reference of the amount of lengthening. Nercessian et al. reported that lengthening by 10% of the length of the femur was safe [10]. However, this report demonstrated neither any scientific basis nor specific incidence of nerve injury. In this study, the patients who presented higher L/F ratios than 8.9 had a high incidence of nerve or soft tissue symptoms. The evaluation of the amount of lengthening by L/F ratio was associated with these symptoms, which means that L/F ratios could be helpful in deciding the optimum amount of acute lengthening in hip arthroplasty. However, among seven patients with nerve complications, there was no statistically significant difference in L/F ratio and GFO change between two cases with partial motor deficit and five cases with temporary sensory disturbance without motor deficit (Table 3). Beyond a certain threshold, acute limb lengthening (for example, lengthening with an L/F ratio 8.9 or more) causes nerve complications. But the amount of lengthening alone is not enough to explain whether nerve damage remains sensory disturbance or at what point it becomes motor deficit. Individual differences of the patients and other unknown factors may be involved in the degree of nerve damage caused by acute lengthening.

It goes without saying that nerve injury in primary THA is not only the result of excessive limb lengthening. Nerve injury may be caused by compression, traction, ischemia, or two or more of these factors. Compressive injury may occur secondary to intra-operative retractor placement or a post-operative haematoma, resulting in a delayed presentation of neurologic injury. Traction injury may be secondary to intra-operative manipulation (including hip dislocation and reduction manoeuvres). However, we think the nerve injury caused by technical or accidental problems such as these can be prevented by a careful and gentle operating procedure. Navarro et al. reduced the incidence of nerve lesions by over 50% in posterior approach by paying increased attention to the sciatic nerve [11].

Many clinical papers have measured the amount of leg lengthening or leg-length discrepancy after THA. Most used a manual procedure, such as drawing lines on the plane radiography. However, such manual procedures often result in measurement error, and the measurement reproducibility is not very reliable. In this study, the measurement method for the amount of lengthening was conventional, but all measurements were performed in digital radiography using computer graphics software, resulting in high reproducibility and low

Table 4 Comparison of patients with motor deficit and with complications without motor deficit

	Patients with motor deficit ($n = 2$)	Patients with complications without motor deficit ($n = 7$)	P value
Mean L/F ratio	10.5 + 1.1	9.8 + 1.9	0.60
Mean change of GFO (mm)	− 8.3 + 0.6	− 6.3 + 17.2	0.14

GFO global femoral offset

Table 5 Comparison of patients with motor deficit and without motor deficit

	Patients with motor deficit ($n = 2$)	Patients without motor deficit ($n = 59$)	P value
Mean L/F ratio	10.5 + 1.1	7.9 + 1.4	0.035
Mean change of GFO (mm)	− 8.3 + 0.6	− 3.9 + 9.9	0.16

GFO global femoral offset

errors. All measurements were digitally calibrated. It is important how to measure the amount of leg lengthening. Various methods using X-ray radiograph exist for measuring limb length after THA, the recent paper described that the distance between the femoral head centre of rotation and the tip of the lesser trochanter was consistent in measuring limb length [12]. However, it was difficult to determine the femoral head centre of rotation in the preoperative radiograph because there were so many cases with deformed femoral head. Thus, we adopted the conventional measurement procedure (using transteardrop line and several anatomical landmarks such as the tip of lesser trochanter) in this study (Fig. 1). In order to reduce the measurement error, we used the almost perfectly well-taken radiographs. Therefore, we think our measurements methodology and data in this study are more accurate than in previous studies.

When acute lengthening is performed in THA, the direction of the leg prolongation is not simply the major axis direction of the lower limbs. Because the GFO changes in addition to the longitudinal change in leg length, nerves and soft tissue are lengthened three-dimensionally. Thus we need to consider not only longitudinal leg lengthening but also lateral GFO change when analyzing soft tissue complications because soft tissue tension after THA with acute lengthening is affected by both factors. However, GFO rarely extends more than several centimeters. In the 61 joints in this study, postoperative GFO slightly decreased as compared with pre-operative GFO in most cases. The mean change of post-operative GFO was − 4.1 mm, and no clear association could be found between the amount of change in GFO and the occurrence of complications. Probably, this is because the change in

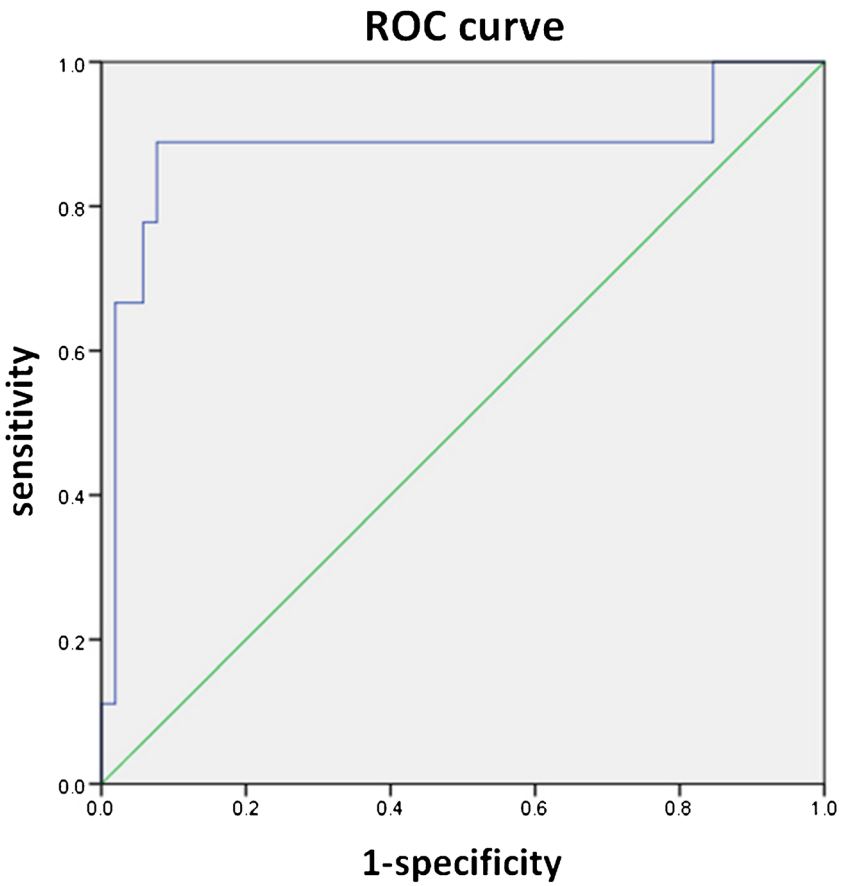

Fig. 4 ROC curve. When the cutoff value of the L/F ratio was set at 8.7, sensitivity was 88.9% and specificity was 92.3%

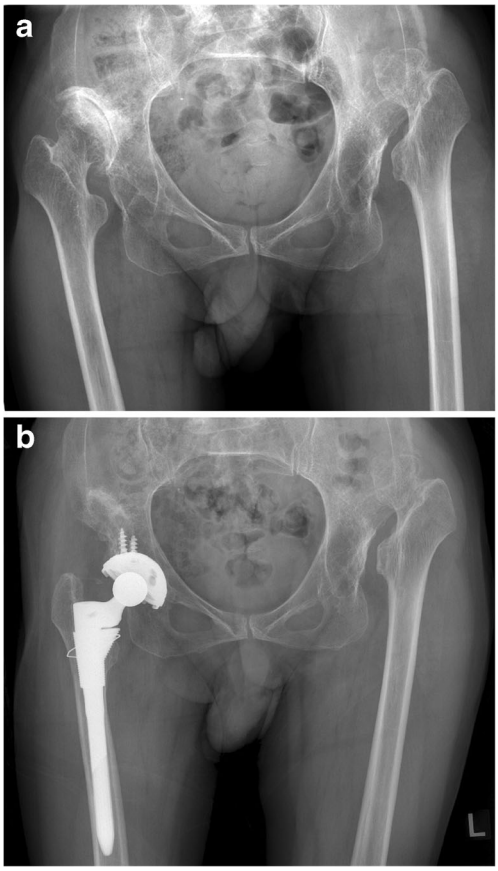

Fig. 5 a) Pre-operative radiography. b) Post-operative radiography. Amount of lengthening, 3.54 cm. Femoral shaft length, 36.1 cm. L/F ratio = 9.8

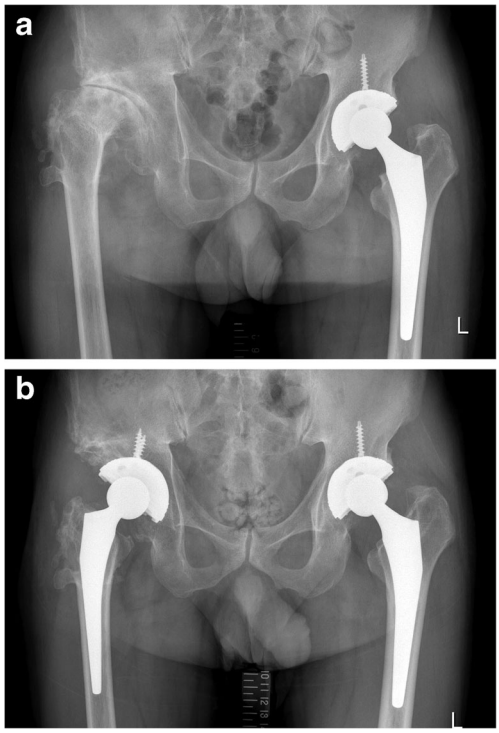

Fig. 6 a) Pre-operative radiography. b) Post-operative radiography. Amount of lengthening, 3.7 cm. Femoral shaft length, 48.5 cm. L/F ratio = 7.6

GFO was not significant compared to the change in longitudinal prolongation. However, the threshold of L/F ratio might change if post-operative GFO becomes obviously longer than pre-operative GFO in most cases. Further, three-dimensional analysis using CT and MRI imagery is expected in future.

It goes without saying that complications associated with acute lengthening in THA should be avoided, and these kinds of complications are usually predictable to some degree depending on the amount of lengthening. We think that L/F ratio will be a useful predictor for such complications. However, once complications occur, the appropriate medical interventions must be considered for recovery. There is some controversy about additional surgical intervention for nerve complications after THA. It has not been well known which kinds of motor deficit can be restored by conservative treatment and which should be treated by additional surgical intervention. Fortunately in this series, we were able to treat all seven nerve complication cases, including two with motor deficits, conservatively. Pritchett recommends an additional surgical procedure if a major nerve injury (sciatic, femoral, or obturator) due to THA does not recover spontaneously [13]. However, the criteria indicating additional surgical intervention were not described concretely. The clear definition of criteria to determine treatment strategies for nerve complications after THA is a future problem.

There were several limitations in this study. First, we did not check for the presence or absence of lumbar degenerative disease in all patients. The presence of lumbar disease may enhance the results. Second, all surgeries were performed by only one surgeon, using the posterior approach. Other approaches or a different surgeon might produce different results. Third, the actual leg was lengthened three-dimensionally, but we measured the distance in just two dimensions. For example, offset measurements on plain radiographs are susceptible to femoral anteversion. The most exact way of measuring the amount of leg lengthening after THA is to use CT-based 3D preoperative planning software, which can exactly measure both horizontal and vertical elongation [14]. However, such a measurement procedure is not common because it needs special software and both pre-operative and post-operative CT data. Fourth, it is possible that we missed subclinical nerve dysfunction. We did not perform perioperative electromyograms and nerve conduction studies in this study. Fifth, we did not evaluate soft tissue contracture as an objective numeric value. Finally, this was a retrospective single-centre study.

Conclusion

This study indicated that L/F ratio can be helpful in avoiding complications caused by acute lengthening in primary THA. The patients who presented higher L/F ratio than 8.7 are at high risk of complications caused by acute limb lengthening in primary THA. In other words, it is risky to perform acute lengthening of more than 8.7% of femoral shaft length when adjusting leg length in THA.

Compliance with ethical standards

This investigational protocol was conducted with the approval of the Kanazawa University Graduate School of Medical Science Ethics Committee.

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