Acta Neurochirurgica (2024) 166:26
https://doi.org/10.1007/s00701-024-05924-3

ORIGINAL ARTICLE

Factors influencing slippage after microsurgical single level lumbar spinal decompression surgery - Are the psoas and multifidus muscles involved? -

Naokado Ikeda[1] · **Kunio Yokoyama**[1] · **Yutaka Ito**[1] · **Hidekazu Tanaka**[1] · **Makoto Yamada**[1] · **Akira Sugie**[1] · **Toshihiro Takami**[2] · **Masahiko Wanibuchi**[2] · **Masahiro Kawanishi**[1]

Received: 26 July 2023 / Accepted: 16 November 2023

Abstract

Purpose Patients with lumbar spinal stenosis (LSS) require microsurgical decompression (MSD) surgery; however, MSD is often associated with postoperative instability at the operated level. Paraspinal muscles support the spinal column; lately, paraspinal volume has been used as a good indicator of sarcopenia. This study aimed to determine preoperative radiological factors, including paraspinal muscle volume, associated with postoperative slippage progression after MSD in LSS patients.

Methods Patients undergoing single-level (L3/4 or L4/5) MSD for symptomatic LSS and followed-up for ≥ 5 years in our institute were reviewed retrospectively to measure preoperative imaging parameters focused on the operated level. Paraspinal muscle volumes (psoas muscle index [PMI] and multifidus muscle index [MFMI]) defined using the total cross-sectional area of each muscle/L3 vertebral body area in the preoperative lumbar axial CT) were calculated. Postoperative slippage in the form of static translation (ST) ≥ 2 mm was assessed on the last follow-up X-ray.

Results We included 95 patients with average age and follow-up periods of 69 ± 8.2 years and 7.51 ± 2.58 years, respectively. PMI and MFMI were significantly correlated with age and significantly larger in male patients. Female sex, preoperative ST, dynamic translation, sagittal rotation angle, facet angle, pelvic incidence, lumbar lordosis, and PMI were correlated with long-term postoperative worsening of ST. However, as per multivariate analysis, no independent factor was associated with postoperative slippage progression.

Conclusion Lower preoperative psoas muscle volume in LSS patients is an important predictive factor of postoperative slippage progression at the operated level after MSD. The predictors for postoperative slippage progression are multifactorial; however, a well-structured postoperative exercise regimen involving psoas muscle strengthening may be beneficial in LSS patients after MSD.

Keywords Lumbar spinal stenosis · Microsurgical decompression · Psoas muscle · Sarcopenia · Spondylolisthesis

Introduction

Degenerative spondylolisthesis is seen on preoperative radiographs of patients who have lumbar spinal stenosis (LSS). The possible clinical consequences of a slipped vertebra have been under debate for decades [14, 18]. When both physiotherapy and medical treatment fail in patients with LSS, surgical intervention in the form of lumbar decompression with or without spinal fusion is considered. However, proper patient selection is crucial for optimal surgical outcomes in LSS patients because decompression alone could lead to postoperative lumbar instability requiring reoperation, whereas decompression with primary fusion is reportedly associated with longer postoperative recovery time, more surgery-related complications, and greater costs [6]. For the patient selection, some preoperative predictors for slippage progression after decompression alone were already reported and these might be helpful. It is reported that preoperative

---

✉ Naokado Ikeda
naokado.ikeda@ompu.ac.jp

[1] Department of Neurosurgery, Neuroendoscope Center, Ijinkai Takeda General Hospital, 28-1 Ishidamoriminamichou, Fushimi, Kyoto 601-1495, Japan

[2] Department of Neurosurgery and Neuroendovascular Surgery, Osaka Medical and Pharmaceutical University, 2-7 Daigaku-Machi, Takatsuki, Osaka 569-8686, Japan

findings associated with instability and slippage at the surgical level, preoperative spinopelvic parameters, and severity of low back pain are related to the postoperative progression of slippage [6, 16, 20, 26]. However, there is still no consensus on the decision for fusion with decompression.

Recently, the concept of frailty has been introduced as a measure of a patient's health status. Unfortunately, the current assessments for measuring human frailty are mostly subjective and require prolonged patient cooperation, which is often impractical [1]. For this purpose, surrogate markers of frailty, such as sarcopenia, may be more useful to clinicians [29]. Morphometrics is used to quantitatively measure sarcopenia and frailty and may better indicate a patient's general health and physiological reserve for tolerating surgery. Among them, cross sectional area measurement of paraspinal and psoas muscle are useful as convenient surrogates for assessment of sarcopenia and frailty [5, 8, 13, 28]. In addition, these muscles play an important role in the stability and functional movement of the lumbar spine [23].

In the present study, we examined radiographical predictive factors, including paraspinal and psoas muscle volumes which are closely related to stability and functional motion of spinal column, for postoperative progression of slippage after single-level microsurgical decompression (MSD) without fusion for LSS and determine whether sarcopenia influences this pathological progression.

Materials and methods

Patient selection

The study protocol was approved by the institutional review board and the Ethics Committee of Ijinkai Takeda General Hospital (approval number: 2021016). We retrospectively reviewed the medical records and radiographical images of patients from our hospital's electronic records who underwent single-level (L3/4 or L4/5) MSD for LSS at our hospital between January 2009 and December 2016 who had not responded to conservative treatment with pharmacotherapy and physiotherapy for low back pain, intermittent claudication, and lower limb pain. Patients were included if the preoperative (< 2 months before the surgery) lumbar magnetic resonance imaging (MRI), computed tomography (CT), and dynamic X-ray images were available, and the patient was followed-up radiographically for at least five years. Patients undergoing revision surgery at the operated level or another spinal surgery, LSS involving vertebral fracture or severe scoliosis, and those with a medical history of spinal tuberculosis or tumor were excluded.

Surgical methods

All patients underwent conventional MSD with bilateral partial laminectomy under general anesthesia in the prone position. After resecting the ligamentum flavum, less than one-third of the medial side of the superior articular process of the vertebral body underneath was removed using an ultrasound aspirator, and the medial side of the pedicle of the vertebral arch was confirmed. At least 10 mm of the cranial end of the vertebral arch was preserved.

Imaging evaluation

Radiological and spinopelvic parameters at the operated level

The following radiological parameters at the operated level were measured from the imaging data: static translation (ST) measured on the preoperative and the last follow-up lumbar sagittal MRI (Fig. 1a); dynamic translation (DT) and sagittal rotation angle (SRA) on preoperative dynamic lumbar X-ray (Fig. 1b, c); disc height (DH) and facet angle (FA) on preoperative axial CT images (Fig. 1d, e); the presence of facet fluid (FF) confirmed on preoperative lumbar MRI (Fig. 1f). Additionally, spinopelvic parameters, including pelvic incidence (PI), lumbar lordosis (LL), and sacral slope (SS), were measured on standing full-spine X-ray images (Fig. 1g).

Based on this data, patients were divided into postoperative progressive slippage (defined as ≥ 2 mm progression in ST in the last follow-up lumbar MRI compared with preoperative ST values) and non-slippage groups.

Paraspinal muscle volume

We assessed central sarcopenia by measuring the cross-sectional area of bilateral psoas and multifidus muscles in the middle of the L3 vertebral body on the axial image of the preoperative lumbar CT scan. Axial image of MRI was routinely taken only at intervertebral disc level and endplate level of each vertebra in our institute. For retrospective assessment, we could not measure the cross-sectional area of these muscles in the middle of the L3 vertebral body with axial MRI image. Therefore, the cross-sectional area of each muscle and the L3 vertebral body was manually outlined on the CT scans and referenced to almost the same level on the axial MRI images obtained from the Picture Archiving and Communication System (PACS) of our institute to trace the correct margin of the muscle as much as possible (Fig. 1h, i); the marked area was automatically calculated. For each patient, we calculated the ratio of the cross-sectional area for bilateral psoas muscles and multifidus muscles area divided

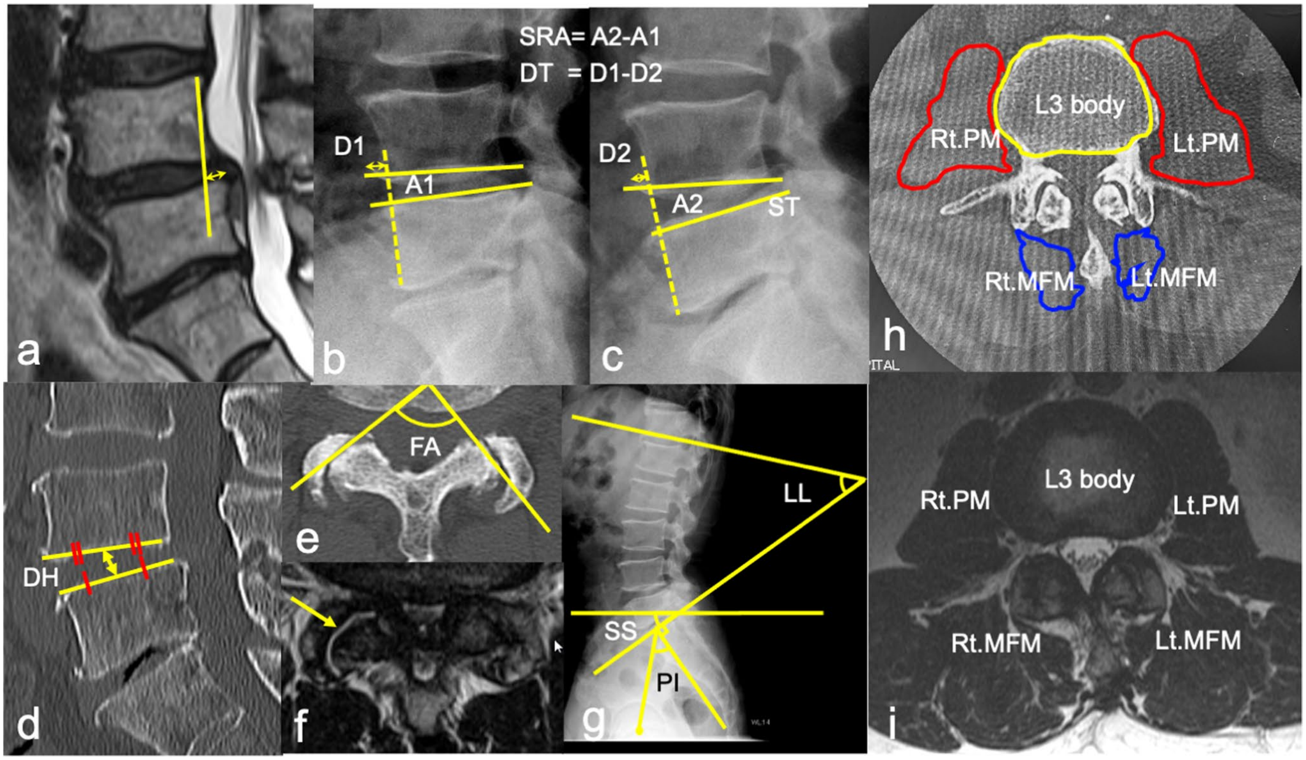


Fig. 1 Measuring methods for spinopelvic and radiological parameters and paraspinal muscle volumes. We measured static translation (ST) on the lumbar spine magnetic resonance imaging (MRI) (**a**), and sagittal rotation angle (SRA) and dynamic translation (DT) at the operated level on dynamic X-ray imaging (**b**, **c**). Disc height (DH) and facet angle (FA) were measured from the preoperative lumbar spine computed tomography (CT) (**d**, **e**). Facet fluid sign (FF, arrow) was measured at the operated level on the lumbar spine MRI (**f**). Preoperative spinopelvic parameters (LL: Lumbar lordosis, SS: Sacral slope, PI: Pelvic incidence) were measured on standing full-spine X-ray images (**g**). The cross-sectional area of the psoas muscle (PM) (enclosed by red line), the multifidus muscle (MFM) (enclosed by blue line), and the L3 vertebral body (enclosed by yellow line) were measured on the preoperative axial CT image with reference to the almost same level axial MRI image (**h**, **i**). For each patient, we calculated the ratio of the cross-sectional area of bilateral psoas muscles and the multifidus muscle divided by the area of the L3 vertebral body; the ratios were represented as the psoas muscle index and multifidus muscle index, respectively

by the cross-sectional area of the L3 vertebral body [10]; the ratios were represented as psoas muscle index (PMI) and multifidus muscle index (MFMI), respectively. To minimize the bias, the patient outcomes were blinded when we measured the muscle volumes in PACS.

Statistical analysis

All data were analyzed using JMP Pro (version 16.2 for Mac; SAS Institute Inc., NC, USA) and presented as mean ± standard deviation or median. Pearson's correlation coefficient and Wilcoxon rank-sum test were used to assess the correlation between patient age, sex, PMI, and MFMI. The postoperative progressive slippage and non-slippage groups were compared using the Wilcoxon rank-sum test, Chi-squared test, and binary logistic regression for the following variables: age, sex, radiographic parameters at the operated level (L3/4 or L4/5), spinopelvic parameters, PMI, and MFMI. A p-value of < 0.05 was considered statistically significant. A Receiver operating characteristic curve was created to determine the PMI cutoff values, as predictors of slippage progression. The accuracy of diagnosis was evaluated by calculating the area under the curve.

Results

Patient demographics

We included a total of 95 patients (54 males, 41 females) who had undergone single-level MSD for LSS with a mean age of 69.0 ± 8.2 years. The mean postoperative follow-up period was 7.51 ± 2.58 years. The majority of patients ($n = 74$) were operated on for L4/5 level LSS whereas 21 patients had L3/4 level LSS (Table 1).

Postoperative slippage progression (> 2-mm translation after ≥ 5 years postoperatively) was observed in 27 patients. The mean age of the postoperative slippage group

Table 1 Demographic data of all patients

Age (years)		69.0 ± 8.21
Sex (n)	male	50
	Female	45
Operated level (n)	L3/4	21
	L4/5	74
Follow duration (year)		7.52 ± 2.58
pre-ST (mm)		2.82 ± 3.13
DH (mm)		8.94 ± 2.08
DT (mm)		1.31 ± 2.15
SRA (°)		7.91 ± 3.75
Facet fluid (n)	(+)	77
	(-)	18
FA (°)		66.2 ± 20.7
PI (°)		53.4 ± 11.2
LL (°)		37.8 ± 12.0
SS (°)		32.7 ± 8.33
PMI		1.02 ± 0.306
MFMI		0.639 ± 0.190

DH disc height, *FA* facet angle, *LL* lumbar lordosis, *MFMI* multifidus muscle index, *PI* pelvic incidence, *PMI* psoas muscle index, *pre-ST* preoperative static translation, *SRA* sagittal rotation angle, *SS* sacral slope

Table 2 Univariate analysis of postoperative slippage progression after single level microsurgical decompression for lumbar spinal stenosis

		Postoperative Slippage Progression		
		(-)	(+)	*p*-value
Age		68.3 ± 0.993	70.5 ± 1.58	0.214
Sex	Male	41	9	
	Female	27	18	0.0176
Operated level	L3/4	3	18	
	L4/5	24	50	0.169
pre-ST (mm)		2.47 ± 0.376	3.71 ± 0.597	0.0419
DH (mm)		8.89 ± 0.253	9.05 ± 0.410	0.843
DT (mm)		0.990 ± 0.259	2.09 ± 0.404	0.00680
SRA (°)		7.41 ± 0.449	9.20 ± 0.721	0.0453
Facet fluid	(+)	1	25	
	(-)	16	52	0.0203
FA (°)		69.0 ± 2.48	59.0 ± 3.98	0.0614
PI (°)		50.7 ± 1.26	60.6 ± 2.07	< 0.0001
LL (°)		35.5 ± 1.41	43.7 ± 2.25	0.00270
SS (°)		31.9 ± 1.02	34.8 ± 1.62	0.0706
PMI		1.08 ± 0.0355	0.875 ± 0.0564	0.00380
MFMI		0.651 ± 0.0231	0.610 ± 0.0366	0.468

DH disc height, *FA* facet angle, *LL* lumbar lordosis, *MFMI* multifidus muscle index, *PI* pelvic incidence, *PMI* psoas muscle index, *pre-ST* preoperative static translation, *SRA* sagittal rotation angle, *SS* sacral slope

was 70.5 ± 1.58 years as compared to 68.3 ± 0.993 for the non-slippage group. There was no statistically significant between-group difference in terms of the patient's age ($p = 0.214$). On the other hand, the two groups displayed a statistically significant difference in terms of the presence of the female sex ($p = 0.017$; slippage group: $n = 18/27$, 66.7%; non-slippage group: $n = 27/68$, 39.7%). In terms of operated vertebral levels, three patients had an L3/4 MSD and 24 patients had an L4/5 MSD in the slippage group, whereas 18 patients underwent an L3/4 MSD and 50 patients had an L4/5 MSD in the non-slippage group. There was no statistically significant between-group difference in terms of the operated spinal levels ($p = 0.169$) (Table 2).

Predictive factors for postoperative slippage progression

Radiological and spinopelvic parameters

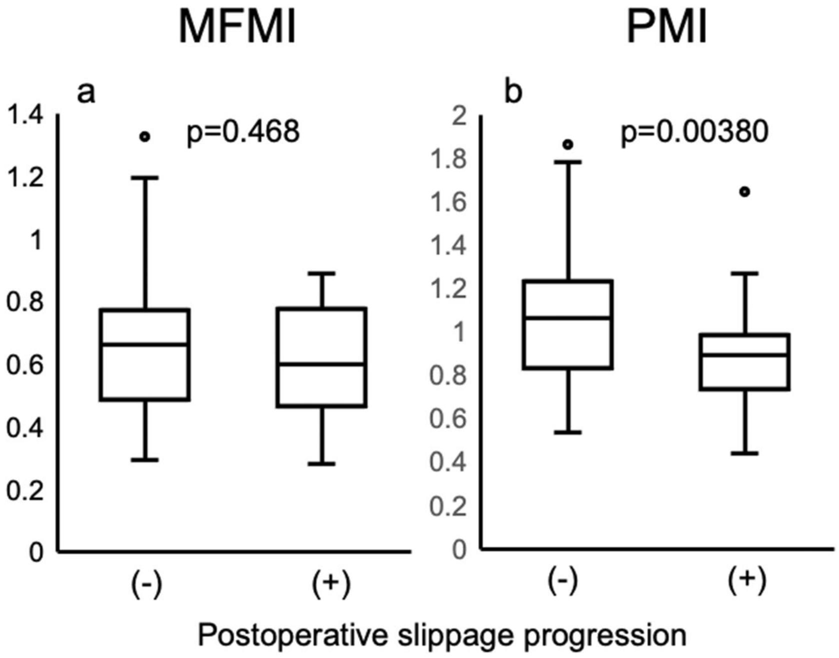
Table 2 presents the results of the univariate analysis for determining predictive factors for postoperative slippage. We found that DH, FA, and SS were statistically similar between the slippage group and the non-slippage groups ($p = 0.843$, $p = 0.061$, and $p = 0.070$, respectively). However, preoperative ST, DT, SRA, PI, and LL were significantly larger in the slippage group compared to the non-slippage group ($p = 0.041$, $p = 0.045$, $p < 0.000$, and $p = 0.002$, respectively). Lastly, the presence of preoperative FF in the operated vertebral was significantly correlated with postoperative slippage ($p = 0.02$).

Paraspinal muscle volumes

We found that PMI was statistically smaller in the slippage group than in the non-slippage group ($p = 0.003$), whereas MFMI was not statistically different between the two groups ($p = 0.468$) (Fig. 2). Figure 3 presented receiver operating characteristic curves for detecting postoperative slippage via preoperative significant radiological factors in the univariate analysis (Fig. 3). A threshold preoperative PMI value of 1.01 distinguished whether slippage progression would occur at the operated level, with a sensitivity of 0.852 and specificity of 0.568 (area under the curve of 0.691).

Factors that were found to be significantly correlated with postoperative slippage in the univariate analysis were further subjected to multivariate logistic regression analysis. We found that none of the aforementioned parameters served as an independent risk factor for slippage progression (Table 3).

Fig. 2 Preoperative paraspinal muscle and psoas muscle index in postoperative slippage group and non-slippage group. Psoas muscle index (PMI) was significantly smaller in the postoperative slippage group than in the non-slippage group. On the other hand, the multifidus muscle index (MFMI) was comparable in both groups”



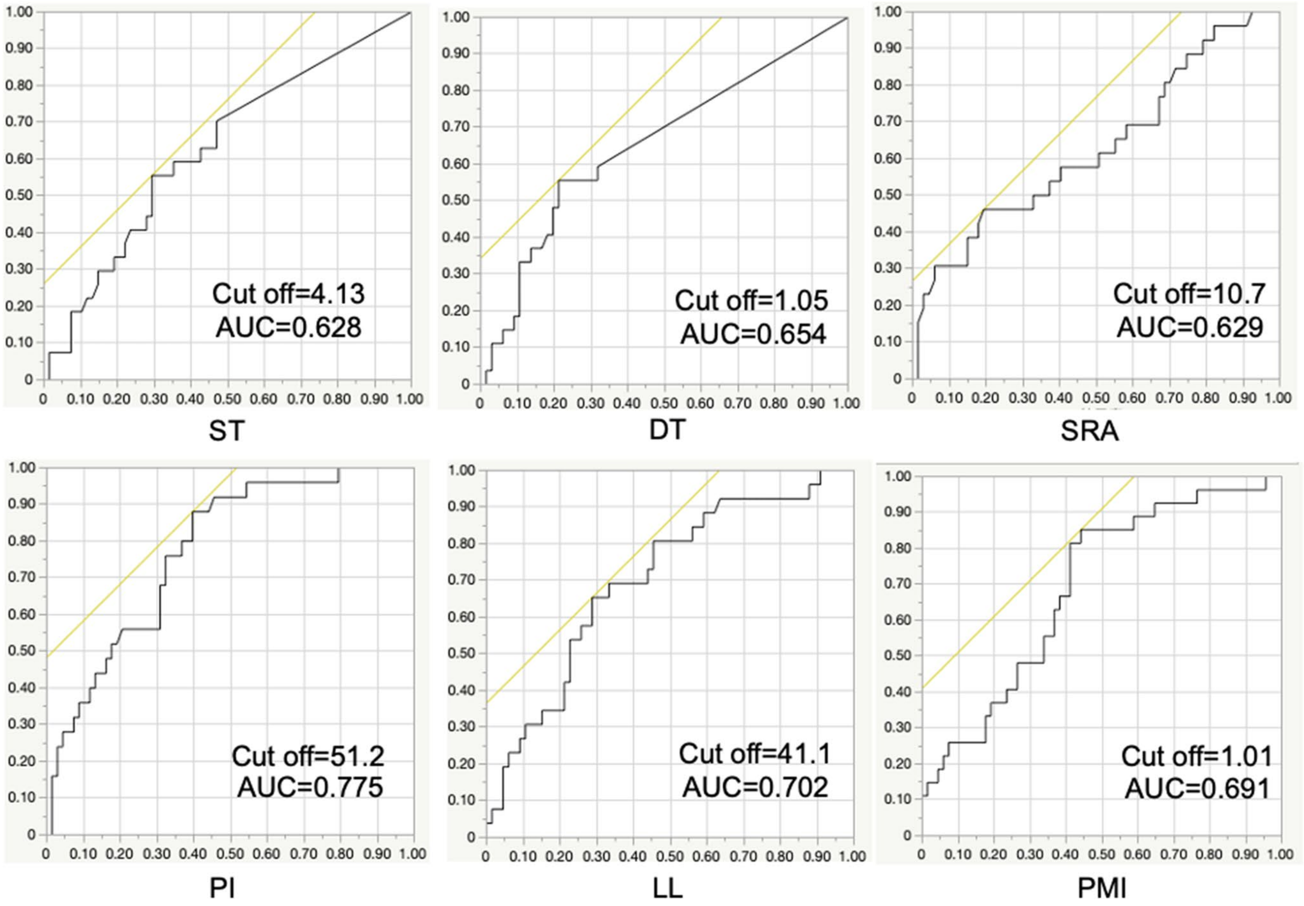


Fig. 3 Receiver operating characteristic (ROC) curves for detecting postoperative slippage via preoperative significant radiological factors in univariate regression analysis. DT; Dynamic translation, LL; Lumbar lordosis, PI; Pelvic incidence, PMI; Psoas muscle index, SRA; Sagittal rotation angle, ST; Static translation

Table 3 Multivariate risk factor analysis of postoperative slippage progression after single level microsurgical decompression for lumbar spinal stenosis

	OR	95%CI	p value
DT (mm)	1.04	0.726–1.491	0.827
pre-ST (mm)	1.06	0.859–1.302	0.596
LL (°)	0.978	0.927–1.032	0.408
Facet fluid (+)	4.32	0.0237–2.27	0.155
Female sex	2.84	0.0879–1.41	0.136
PMI	1.24	0.965–1.58	0.0768
PI	0.942	0.881–1.01	0.0655
SRA (°)	0.845	0.701–1.02	0.0639

LL lumbar lordosis, *MFMI* multifidus muscle index, *PI* pelvic incidence, *PMI* psoas muscle index, *pre-ST* preoperative static translation, *SRA* sagittal rotation angle, *SS* sacral slope

Paraspinal and psoas muscle volume measurement

The mean paraspinal muscle volume, defined as PMI and MFMI, of the 95 patients was observed as 0.969 ± 0.306 and 0.634 ± 0.190 respectively. Both PMI and MFMI were significantly greater in male patients (1.17 ± 0.308 and 0.671 ± 0.163, respectively) compared to female patients (0.863 ± 0.212 and 0.604 ± 0.213, respectively) (Fig. 4a, b). Furthermore, each index showed a statistically significant negative correlation with the patient's age (Fig. 4c, d).

Discussion

Instability including preoperative slippage at the operative levels is one of the most common indications for reoperation following decompression [17]. However, in patients with LSS and degenerative spondylolisthesis, there is a lack of consensus on whether decompression surgery with fusion is superior to decompression without fusion despite the results of three randomized controlled trials [3, 9, 12].

It is well-known that preoperative findings associated with instability, such as FF collection, disc degeneration including reduced DH, and slippage at the surgical level, are related to the postoperative progression of slippage and are deemed as predictive factors for postoperative instability after MSD for LSS [6]. Some authors have also reported preoperative severity of low back pain as an important predictor of postoperative progression of spondylolisthesis [6, 26]. Furthermore, spinopelvic parameters reportedly have a substantial impact on lumbar spinal stability, i.e. SS, PI, SRA, and LL were related to degenerative lumbar spondylolisthesis and positively associated with the extent of slippage [16, 20]. Likewise, in the present study, apart from SS and DH, preoperative ST, DT, FF collection, PI, SRA, and LL were associated with postoperative slippage progression.

The role of paraspinal muscles in the stability and functional movement of the lumbar spine is well-established [23]. In a recent report, Getzmann et al. demonstrated that fatty infiltration in these muscles was associated with higher disability and worse health-related quality of life in LSS patients [11]. On the other hand, Demitriou et al. demonstrated that the degree of fatty infiltration in multifidus could not predict treatment failure (defined as conversion to a fusion according to postoperative slippage progression) following decompression surgery for degenerative LSS [6]. Regarding the psoas muscle, Park et al. reported that the psoas muscle volumes, along with the multifidus, were well correlated with the degree of slippage in the isthmic spondylolisthesis group, but not in the degenerative spondylolisthesis group [24]. Likewise, Aoki et al. reported that progression of L5 vertebral slip was correlated with atrophy of psoas muscles, but not with that of paraspinal muscles [2]. It is noteworthy that none of these reports included surgically treated patients. In contrast, the present study revealed that a decrease in psoas muscle volume (PMI) was significantly associated with postoperative slippage progression in the long run (mean follow-up period = 7.51 ± 2.58 years); there was no statistically significant association between MFMI and postoperative slippage progression. This is the first report to examine a possible relationship between paraspinal and psoas muscle volume and postoperative slippage in LSS patients undergoing MSD. Unfortunately, present study could not demonstrate the independent predictive value of these muscle volumes for postoperative slippage progression following MSD. And, especially in paraspinal muscle or psoas volumes and fatty degeneration, the results vary depending on each report as noted above. These results suggest that spondylolisthesis after MSD is a multifactorial pathology involving these factors.

Sarcopenia is characterized by low muscle mass with reduced muscle strength and physical performance, and is a major component of the frailty syndrome, both being considered strong predictors of morbidity, disability, and death in older people [21]. Lately, the influence of sarcopenia in spinal disorders has attracted much attention not only regarding spinal malalignment and vertebral osteoporotic fractures but also in surgical outcomes of lumbar spine degenerative disease [7, 19]. While the gold standard for quantifying muscle mass is with biological impedance analysis and dual-energy X-ray absorptiometry, several studies have used imaging modalities for measuring psoas muscle mass as morphometrics [4]. Morphometrics involves the measurement of patient attributes that are indicative of sarcopenia, and frailty by proxy. In recent years, measuring the cross-sectional area of the psoas muscle has become a popular method for morphometric analysis because of its relation to poor overall

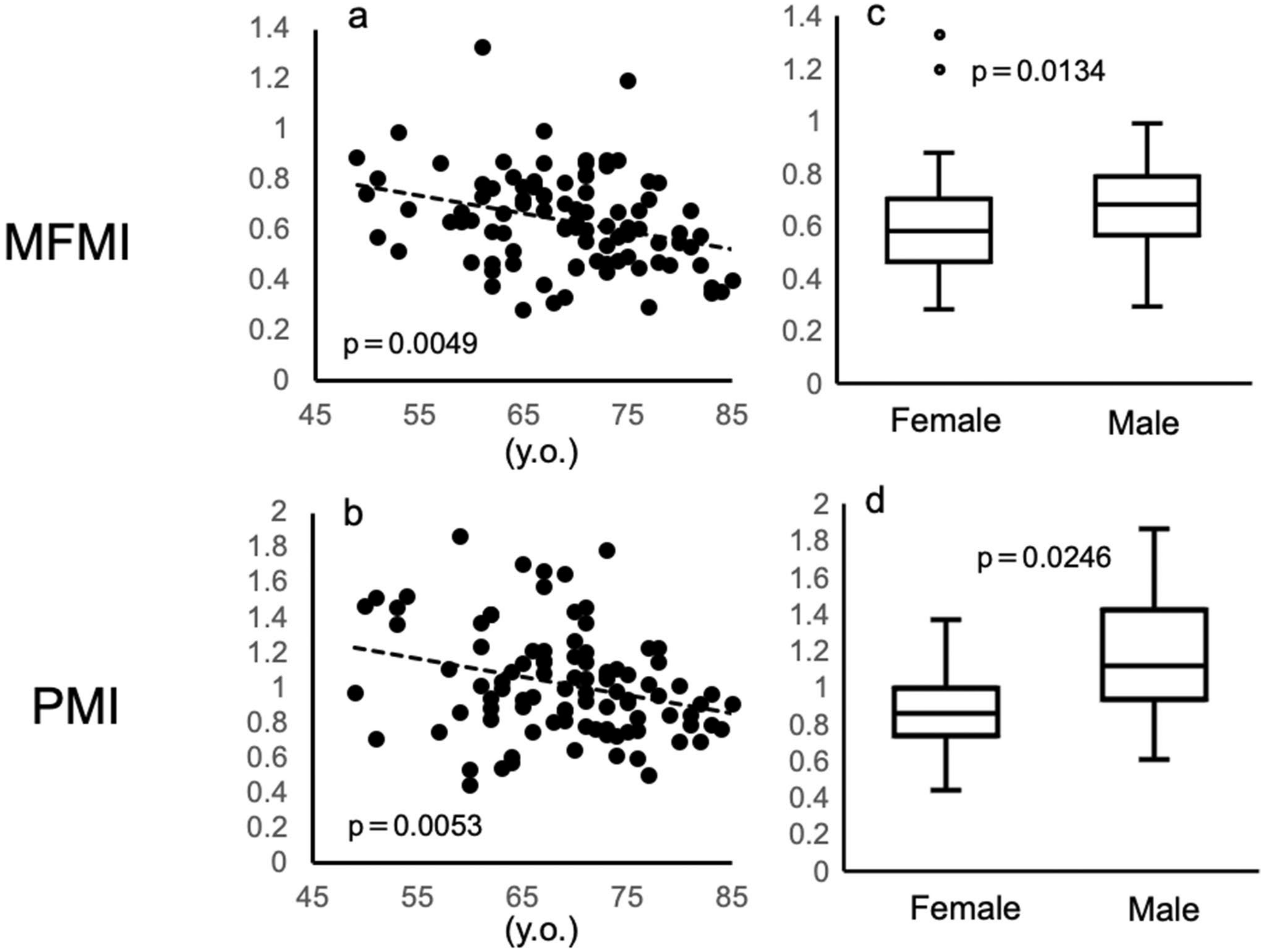


Fig. 4 The relationship between paraspinal muscle indexes and patient's age and sex. Multifidus muscle index (MFMI) and psoas muscle index (PMI) were negatively correlated with the patient's age (**a, b**), and each index was significantly larger in male patients (**c**, **d**)

survival or surgical outcomes in patients with cancer. A meta-analysis and systematic review reported that lean skeletal muscle mass was associated with shorter overall survival in cancer patients [15, 25, 27]. These results support our methodological strategy of using PMI and MFMI as convenient surrogates for the assessment of sarcopenia and frailty. Based on these results, we can suggest that systemic sarcopenia or preoperative frailty may influence the prognosis of spondylolisthesis after MSD in patients with LSS; however, further studies involving more direct assessments are warranted to prove a causal relation.

Limitations

First, we used a retrospective study design to include data from a single institution; the retrospective nature of the measurements may have introduced observer bias. However, the measured paraspinal muscle indexes (PMI and MFMI) were well correlated with patients' age and sex which is consistent (Fig. 4). These results are consistent with previous reports [22]. This suggests our measurement methods were reliable and observer bias was minimized. Second, this study included a small subject sample because it included patients who were followed-up radiologically for at least five years, and excluded patients who were lost to follow-up in less than five years. Dynamic X-rays and CT were performed routinely in almost all patients before MSD for LSS to check for instability and to simulate the bone morphology and postoperative MRI were followed with about 1 year interval for the detection of adjacent spinal disorders in our institute. However, postoperatively, some patients without postoperative complains and complication stopped postoperative MRI follow-up themselves. We cannot rule out the possibility that patients who were excluded may involve many patients with good progress.

Conclusion

In this study, we used PMI as a surrogate measure for evaluating sarcopenia, which is a major component of the frailty syndrome. We found that lower PMI is an important predictive factor for postoperative slippage progression after MSD for LSS. The predictors for postoperative slippage progression are multifactorial; however, a well-structured postoperative exercise regimen involving psoas muscle strengthening may be beneficial in LSS patients after MSD.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00701-024-05924-3.

Acknowledgements The authors would like to thank Enago (www.enago.jp) for the English language review.

Authors' contributions Conceptualization and design: Naokado Ikeda and Kunio Yokoyama; Drafting the article: Naokado Ikeda; Acquisition of data and Analysis: Naokado Ikeda, Yutaka Ito, HIdekazu Tanaka, Makoto Yamada and Akira Sugie; Writing-review and editing: Kunio Yokoyama, Akira Sugie and Masahiro Kawanishi; Supervision: Toshihiro Takami, Masahiko Wanibuchi and Masahiro Kawanishi.

Funding The authors did not receive support from any organization for the submitted work.

Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The study protocol was approved by the institutional review board and the Ethics Committee of Ijinkai Takeda General Hospital (approval number: 2021016).

Consent to participate Informed consent was deemed unnecessary (retrospective cohort study).

Consent for publication Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Amrock LG, Deiner S (2014) The implication of frailty on preoperative risk assessment. Curr Opin Anaesthesiol 27:330–335
2. Aoki Y, Kubota G, Inoue M, Takahashi H, Watanabe A, Nakajima T, Sato Y, Nakajima A, Saito J, Eguchi Y, Orita S, Fukuchi H, Sakai T, Ochi S, Yanagawa N, Nakagawa K, Ohtori S (2021) Age-specific characteristics of lumbopelvic alignment in patients with spondylolysis: how bilateral L5 spondylolysis influences lumbopelvic alignment during the aging process. World Neurosurg 147:e524–e532
3. Austevoll IM, Hermansen E, Fagerland MW, Storheim K, Brox JI, Solberg T, Rekeland F, Franssen E, Weber C, Brisby H, Grundnes O, Algaard KRH, Boker T, Banitalebi H, Indrekvam K, Hellum C, Investigators N-D (2021) Decompression with or without fusion in degenerative lumbar spondylolisthesis. N Engl J Med 385:526–538
4. Bourassa-Moreau E, Versteeg A, Moskven E, Charest-Morin R, Flexman A, Ailon T, Dalkilic T, Fisher C, Dea N, Boyd M, Paquette S, Kwon B, Dvorak M, Street J (2020) Sarcopenia, but not frailty, predicts early mortality and adverse events after emergent surgery for metastatic disease of the spine. Spine J 20:22–31
5. Chu LP, Chen KT, Lu HK, Lai CL, Huang HC, Hsieh KC (2023) Preliminary study on the application of bioimpedance analysis to measure the psoas major muscle in older adults. PLoS ONE 18:e0275884. https://doi.org/10.1371/journal.pone.0275884
6. Dimitriou D, Winkler E, Weber S, Haupt S, Betz M, Farshad M (2023) A simple preoperative score predicting failure following decompression surgery for degenerative lumbar spinal stenosis. Spine (Phila Pa 1976) 48:610–616
7. Eguchi Y, Suzuki M, Yamanaka H, Tamai H, Kobayashi T, Orita S, Yamauchi K, Suzuki M, Inage K, Fujimoto K, Kanamoto H, Abe K, Aoki Y, Toyone T, Ozawa T, Takahashi K, Ohtori S (2017) Associations between sarcopenia and degenerative lumbar scoliosis in older women. Scoliosis Spinal Disord 12:9. https://doi.org/10.1186/s13013-017-0116-0
8. Englesbe MJ, Lee JS, He K, Fan L, Schaubel DE, Sheetz KH, Harbaugh CM, Holcombe SA, Campbell DA Jr, Sonnenday CJ, Wang SC (2012) Analytic morphomics, core muscle size, and surgical outcomes. Ann Surg 256:255–261
9. Forsth P, Olafsson G, Carlsson T, Frost A, Borgstrom F, Fritzell P, Ohagen P, Michaelsson K, Sanden B (2016) A randomized, controlled trial of fusion surgery for lumbar spinal stenosis. N Engl J Med 374:1413–1423
10. Gakhar H, Dhillon A, Blackwell J, Hussain K, Bommireddy R, Klezl Z, Williams J (2015) Study investigating the role of skeletal muscle mass estimation in metastatic spinal cord compression. Eur Spine J 24:2150–2155
11. Getzmann JM, Ashouri H, Burgstaller JM, Valeri F, Winklhofer S, Ulrich NH, Guggenberger R (2023) The effect of paraspinal fatty muscle infiltration and cumulative lumbar spine degeneration on the outcome of patients with lumbar spinal canal stenosis: analysis of the lumbar stenosis outcome study (LSOS) data. Spine (Phila Pa 1976) 48:97–106
12. Ghogawala Z, Dziura J, Butler WE, Dai F, Terrin N, Magge SN, Coumans JV, Harrington JF, Amin-Hanjani S, Schwartz JS, Sonntag VK, Barker FG 2nd, Benzel EC (2016) Laminectomy plus fusion versus laminectomy alone for lumbar spondylolisthesis. N Engl J Med 374:1424–1434
13. Gomindes AR, Appleton JP, Chugh R, Welch C (2021) Muscle quantity at C3 and/or L3 on routine trauma series computed tomography correlate with brain frailty and clinical frailty scale: a cross-sectional study. Cureus 13:e15912. https://doi.org/10.7759/cureus.15912
14. Hasegawa K, Kitahara K, Shimoda H, Ishii K, Ono M, Homma T, Watanabe K (2014) Lumbar degenerative spondylolisthesis is not always unstable: clinicobiomechanical evidence. Spine (Phila Pa 1976) 39:2127–2135
15. Hida T, Shimokata H, Sakai Y, Ito S, Matsui Y, Takemura M, Kasai T, Ishiguro N, Harada A (2016) Sarcopenia and sarcopenic leg as potential risk factors for acute osteoporotic vertebral fracture among older women. Eur Spine J 25:3424–3431
16. Inose H, Kato T, Onuma H, Morishita S, Matsukura Y, Yuasa M, Hirai T, Yoshii T, Okawa A (2021) Predictive factors affecting surgical outcomes in patients with degenerative lumbar spondylolisthesis. Spine (Phila Pa 1976) 46:610–616
17. Javalkar V, Cardenas R, Tawfik TA, Khan IR, Bollam P, Banerjee AD, Nanda A (2011) Reoperations after surgery for lumbar spinal stenosis. World Neurosurg 75:737–742

18. Johnsson KE, Redlund-Johnell I, Uden A, Willner S (1989) Preoperative and postoperative instability in lumbar spinal stenosis. Spine (Phila Pa 1976) 14:591–593
19. Katsu M, Ohba T, Ebata S, Oba H, Koyama K, Haro H (2020) Potential role of paraspinal musculature in the maintenance of spinopelvic alignment in patients with adult spinal deformities. Clin Spine Surg 33:E76–E80
20. Nakamae T, Nakanishi K, Kamei N, Adachi N (2019) The correlation between sagittal spinopelvic alignment and degree of lumbar degenerative spondylolisthesis. J Orthop Sci 24:969–973
21. Nascimento CM, Ingles M, Salvador-Pascual A, Cominetti MR, Gomez-Cabrera MC, Vina J (2019) Sarcopenia, frailty and their prevention by exercise. Free Radic Biol Med 132:42–49
22. Ni X, Jiao L, Zhang Y, Xu J, Zhang Y, Zhang X, Du Y, Sun Z, Wang S (2021) Correlation between the distribution of abdominal, pericardial and subcutaneous fat and muscle and age and gender in a middle-aged and elderly population. Diabetes Metab Syndr Obes 14:2201–2208
23. Nizard RS, Wybier M, Laredo JD (2001) Radiologic assessment of lumbar intervertebral instability and degenerative spondylolisthesis. Radiol Clin North Am 39(55–71):v–vi
24. Park JH, Kim KW, Youn Y, Kim H, Chung WS, Song MY, Cho JH (2019) Association of MRI-defined lumbar paraspinal muscle mass and slip percentage in degenerative and isthmic spondylolisthesis: A multicenter, retrospective, observational study. Medicine (Baltimore) 98:e18157. https://doi.org/10.1097/MD.0000000000018157
25. Reisinger KW, van Vugt JL, Tegels JJ, Snijders C, Hulsewe KW, Hoofwijk AG, Stoot JH, Von Meyenfeldt MF, Beets GL, Derikx JP, Poeze M (2015) Functional compromise reflected by sarcopenia, frailty, and nutritional depletion predicts adverse postoperative outcome after colorectal cancer surgery. Ann Surg 261:345–352
26. Schonnagel L, Caffard T, Zhu J, Tani S, Camino-Willhuber G, Amini DA, Haffer H, Muellner M, Guven AE, Chiapparelli E, Arzani A, Amoroso K, Shue J, Duculan R, Zippelius T, Sama AA, Cammisa FP, Girardi FP, Mancuso CA, Hughes AP (2023) Decision-making algorithm for the surgical treatment of degenerative lumbar spondylolisthesis of L4/L5. Spine (Phila Pa 1976)
27. Shachar SS, Williams GR, Muss HB, Nishijima TF (2016) Prognostic value of sarcopenia in adults with solid tumours: a meta-analysis and systematic review. Eur J Cancer 57:58–67
28. Tucker BM, Hsu FC, Register TC, Xu J, Smith SC, Murea M, Bowden DW, Freedman BI, Lenchik L (2019) Psoas and Paraspinous muscle measurements on computed tomography predict mortality in European Americans with type 2 diabetes mellitus. J Frailty Aging 8:72–78
29. Zakaria HM, Schultz L, Mossa-Basha F, Griffith B, Chang V (2015) Morphometrics as a predictor of perioperative morbidity after lumbar spine surgery. Neurosurg Focus 39:E5. https://doi.org/10.3171/2015.7.FOCUS15257