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The adaptive changes in muscle coordination following lumbar spinal fusion

Ting-Yun Wang [a,1], Jwo-Luen Pao [b,c,1], Rong-Sen Yang [d], Jyh-Shing Roger Jang [e], Wei-Li Hsu [a,f,*]

[a] *School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Taipei, Taiwan*
[b] *Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan*
[c] *Division of Minimally Invasive Spine Surgery & Orthopedic Surgery, Department of Surgery, Far Eastern Memorial Hospital, New Taipei, Taiwan*
[d] *Department of Orthopedics, National Taiwan University & Hospital, Taipei, Taiwan*
[e] *Department of Computer Science & Information Engineering, National Taiwan University, Taiwan*
[f] *Physical Therapy Center, National Taiwan University Hospital, Taipei, Taiwan*

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ABSTRACT

Limited back motion and damage of paraspinal muscles after spinal fusion surgery may lead to abnormal compensatory movements of the body. Whether neuromuscular control changes after surgery remains unclear. The purpose of the study was to identify the muscle activation patterns employed before and after lumbar spinal fusion. Nineteen patients having low back pain and undergoing minimally invasive lumbar spinal fusion were evaluated at 1 day before and 1 month after fusion surgery. Nineteen matched healthy participants were recruited as controls. Patients' pain severity and daily activity functioning were recorded. All participants were instructed to perform forward reaching, and the muscle activities were monitored using surface electromyography (EMG) with sensors placed on both sides of their trunk and lower limbs. The muscle activation patterns were identified using the principal component analysis (PCA). All patients had significant improvements in pain intensity and daily activity functioning after surgery, but exhibited an adaptive muscle activation pattern during forward reaching movement compared with the controls. Significant loading coefficients in the dominant movement pattern (reflected in the first principal component) were observed in back muscles for controls whereas in leg muscles for patients, both pre- and

* Corresponding author at: Room 326, Floor 3, No.17, Xuzhou Rd., Zhongzheng District, Taipei, Taiwan.
E-mail address: wlhsu@ntu.edu.tw (W.-L. Hsu).
[1] The first two authors contributed equally to this work.

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postoperatively. Despite substantial improvements in pain intensity and daily activity functioning after surgery, the patients exhibited decreased paraspinal muscle activities and adaptive muscle coordination patterns during forward reaching. They appeared to rely mainly on their leg muscles to compensate for their insufficient paraspinal muscle function. Early intervention focusing on training paraspinal muscles should be considered after spinal fusion surgery.

1. Introduction

Spinal fusion is a surgical procedure used to fuse two or more vertebrae and to stabilize the unstable spine segment. Lumbar spinal fusion surgery has been widely used to manage the pain and neurological symptoms in low back pain (LBP) patients (Frymoyer & Catsbaril, 1991). A successful spinal fusion procedure can assist in decreasing pain and improving function associated with spondylolisthesis and degenerative disc disease of the lumbar spine (Carreon, Glassman, & Howard, 2008; Park & Foley, 2008; Phillips, Slosar, Youssef, Andersson, & Papatheofanis, 2013).

The reduced pain severity and improved function after lumbar spinal fusion surgery can be significant (Carreon et al., 2008; Phillips et al., 2013). However, limited back motion after spinal fusion may incur compensatory movements of the adjacent levels, thereby accelerating their degeneration (Chen et al., 2001; Deyo, Nachemson, & Mirza, 2004; Phillips, Carlson, Bohlman, & Hughes, 2000). In addition, paraspinal muscle damage resulting from surgical procedures can induce muscle atrophy and fatty infiltrations (Fan et al., 2010). With increased awareness of the active roles of paraspinal muscles in stabilizing the spine (Ward et al., 2009), minimally invasive spinal fusion has been introduced to minimize the extent of the damage to the paraspinal muscles and adjacent tissues, and as a result substantially decrease postoperative pain and the length of hospital stay. (Dhall, Wang, & Mummaneni, 2008; Isaacs et al., 2005; Schwender, Holly, Rouben, & Foley, 2005; Tsutsumimoto, Shimogata, Ohta, & Misawa, 2009).

A balanced interaction among active (i.e., contractile tissues such as muscles and tendons), passive (i.e., the bony structure comprising the spine and ligaments), and neuromuscular (i.e., the neural control center and mechanoreceptors) subsystems has been suggested to be essential to maintain spinal stability (Panjabi, 1992a,b). Damage to or dysfunction in one subsystem has been suggested to require the other two systems to compensate and may result in alteration in movement coordination for spinal stability. Regarding multi-joint coordination in spinal control, both biomechanical models and empirical evidence show that a combination of spinal muscle forces and appropriately timed muscle activity has been found to be necessary to maintain ideal spinal functional during movements (Cholewicki & McGill, 1996; Granata & Wilson, 2001). An altered lumbar and pelvis coordination in patients with LBP has also been shown during trunk forward bending (Esola, McClure, Fitzgerald, & Siegler, 1996; Silfies, Bhattacharya, Biely, Smith, & Giszter, 2009; Wong & Lee, 2004), rising from the chair (Shum, Crosbie, & Lee, 2007), and walking (Lamoth et al., 2002). Previous research has found that the altered inter-segmental movement of the lumbar and pelvis could be explained by lack of adequate control of trunk extensors and potential trunk extensor muscle dysfunction (Silfies et al., 2009). In terms of spinal function, minimally invasive spinal fusion may help to restore the function of passive spinal structure without extensive dissection of the active structure, such as paraspinal muscles. More importantly, the individuals after such a surgical procedure may resume daily activities in a short amount of time. However, it remains unclear whether the neuromuscular control in daily activities would be affected after the minimally invasive lumbar spinal fusion, especially in the early postoperative phase (Introduction S1).

The purpose of this study was to identify the muscle coordination patterns during commonly performed functional activities, such as a forward reaching task, after minimally invasive lumbar spinal fusion. During forward reaching, the back muscles contract to overcome the gravitational effect of the trunk; thus, this task is considered challenging for people with LBP (Carlsöö, 1961). We hypothesized that patients who underwent lumbar spinal fusion would have impaired function of their back muscles, and thus, required recruitment of different muscle activation patterns for compensation. Specifically, the principal component analysis (PCA) would be applied to detect relevant muscle groups (from a large number of muscle groups) required to represent the main feature of the forward reaching movement (Daffertshofer, Lamoth, Meijer, & Beek, 2004). The results of the PCA would identify the differences between the patients and healthy controls regarding the muscle group combinations (i.e., muscle coordination patterns) employed in the forward reaching movement.

2. Methods

2.1. Participants

We recruited 19 patients with LBP who underwent minimally invasive transforaminal lumbar interbody fusion (Mini-TLIF) in a medical center and 19 age- and gender-matched healthy controls in this study (Table 1). A sample size of 19 was set to ensure that we had 80% power to detect significant differences in paraspinal muscle activities between the control and patient groups based on our pilot electromyography (EMG) data. The inclusion criteria for the participants were as follows: (1) aged between 45 and 80 years; (2) able to stand independently and walk without an assistive device; and (3) presence of LBP caused by degenerative spondylolisthesis or degenerative disc disease diagnosed by the orthopaedic surgeon. The exclusion criteria were as follows: (1) patients who had undergone a previous spinal surgery, (2) other comorbid neurological or musculoskeletal disorders that may affect balance and activity, (3) leg length discrepancies more than 2 cm, and (4) a body mass index greater than 30 kg/m^2. The research procedures were explained to each participant, and informed consent was obtained prior to initiating the research process. The study protocol was approved by the institutional review board.

2.2. Clinical evaluation

The evaluation protocol is shown in Fig. 1. An evaluation of the following variables was conducted for the patient group 1 day before and 1 month after surgery (pre-op and post-op): pain intensity, daily activity functioning, straight-leg-raise test (SLRT), back muscle strength, and muscle activity during the forward reaching movement. The last 3 variables for controls were evaluated once (Fig. 1). The SLRT was performed bilaterally to examine hamstring flexibility (Cameron, Bohannon, & Owen, 1994). Pain intensity was evaluated using a visual analog scale (VAS), which consisted of a horizontal line from 0 to 10, with 0 denoting no pain and 10 denoting maximum pain. The VAS has been found to possess high validity (95% confidence interval = 0.96–0.98) for evaluating acute pain (Bijur, Silver, & Gallagher, 2001). Daily activity functioning was evaluated using the Chinese version of the modified Oswestry disability index (ODI), which has shown satisfactory validity and reliability for evaluating

Table 1
Demographic data of the participants.

	Control group (mean ± SD)	Patient group (mean ± SD)	*P* value
Age (years)	60 ± 12	61 ± 12	$P = .737$
Sex	8 men, 11 women ($n = 19$)	10 men, 9 women ($n = 19$)	$P = .516$
Height (cm)	160 ± 7	160 ± 8	$P = .974$
Weight (kg)	61 ± 10	67 ± 11	$P = .078$
Levels of fusion surgery		L2–4 ($n = 1$) L3–4 ($n = 1$) L3–5 ($n = 2$) L4–5 ($n = 13$) L5–S1 ($n = 2$)	

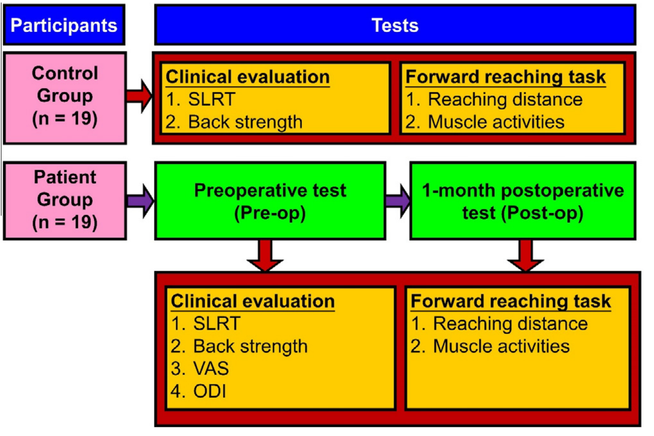

Fig. 1. The experimental protocol for the patient and control groups. The patient group was assessed before and 1 month after surgery (pre-op and post-op) regarding their pain intensity (visual analog scale, VAS), daily activity functioning (Oswestry disability index, ODI), single-leg-raise test (SLRT), and back muscle strength. During clinical evaluations, their muscle activities during the forward reaching movement were recorded. The control group was evaluated once for SLRT and back strength in a clinical evaluation where they performed the same forward reaching task.

patients with chronic LBP (Chow & Chan, 2005). The ODI comprises 10 items and 6 scales (0–5) that quantify the disability in daily activities facing LBP patients. The total ODI score obtained by each individual was divided by 50 (the total possible score) and multiplied by 100 to provide a percentage score, with higher score indicating increased levels of functional disability. The back muscle strength was measured using a back extensor dynamometer, which consisted of a scale connected to a metal plate by an adjustable chain. During the test, the participants were instructed to first stand on the plate with their trunk leaning slightly forward, with both hands grasping the scale of the dynamometer, and then straighten their back. The maximum effort was recorded as their back muscle strength.

2.3. Forward reaching task

The participants were instructed to perform the forward reaching movement starting in a comfortable standing position, with feet shoulder-width apart, both arms raised to shoulder level with elbows fully extended (starting position, Fig. 2A). During forward reaching, the participants were asked to first

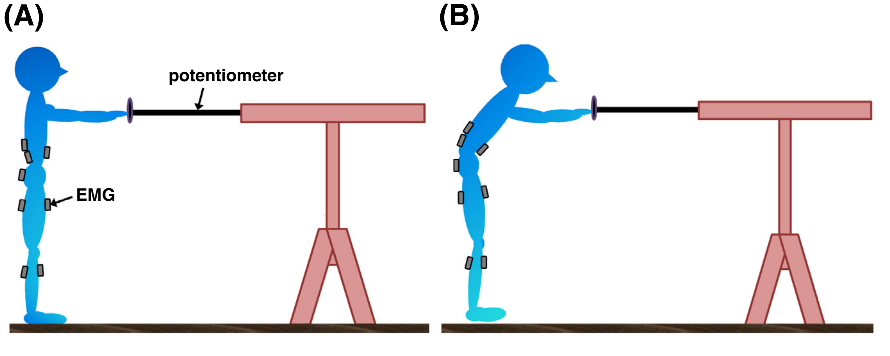

Fig. 2. Experimental setup for the forward reaching task. (A) Starting position (baseline): the participants stood with feet shoulder-width apart, both arms raised to shoulder level with elbows fully extended, and maintained the position for 3 s. (B) Reaching movement: the participants used both hands to push a linear potentiometer forward as far as possible at their self-selected speed (reaching phase), and then maintained the end-range position for 5 s.

maintain the starting position for 3 s (baseline), use both hands to push a linear potentiometer (KTC600, Regal, Sweden) forward as far as possible at their self-selected speed (reaching phase, Fig. 2B), and then maintain the end-range position for 5 s (see Supplementary material). The reaching distance was measured using a linear potentiometer comprising a 600-mm linear position sensor. Five forward reaching trials were collected for each patient for further analysis.

2.4. Muscle activities

The activities of 8 muscle pairs during forward reaching movement were monitored using wireless surface EMG (Trigno™ Wireless System, Delsys, U.S.). The 8 muscles were the rectus abdominis (RA), rectus femoris (RF), tibialis anterior (TA), erector spinae (ES), multifidus (MUL), gluteus maximus (GM), biceps femoris (BF), and the medial head of the gastrocnemius (MEG). The electrode placement for each muscle was as follows (Cholewicki & McGill, 1996; Cram, Kasman, & Holtz, 1998). RA: 3 cm lateral to the umbilicus; RF: midway between the knee and anterior superior iliac spine; TA: at one-third to one-fourth of the distance between the knee and lateral malleolus; ES: 3 cm lateral to the third lumbar spinal process; MUL: 1 cm lateral to the fifth lumbar spinal process; GM: midway between the gluteal trochanter and the sacral vertebrae; BF: one-third proximal of the lateral thigh; and MEG: on the muscle belly of the medial head of the gastrocnemius.

2.5. Data collection and reduction

The potentiometer and EMG data were collected at 1000 Hz using a 64-channel, 12-bit, analog-to-digital converter (National Instruments, U.S.), and were synchronized at the start of data collection. The displacement and velocity of the linear potentiometer were calculated to determine the reaching distance (normalized by foot length), and the start and stop time of the reaching movement (set at the time when the reaching velocity was either greater or less than 10% of the peak velocity). The forward reaching distance was then normalized to the foot length for inter-subject comparisons (Kozak, Ashton-Miller, & Alexander, 2003). The EMG signals were amplified ($\times$1000, CMRR > 80 dB) and band-pass filtered at 10–450 Hz, and then low-pass filtered using a second-order Butterworth filter with a 50-Hz cut-off frequency (Krishnamoorthy, Goodman, Zatsiorsky, & Latash, 2003). Changes in the activity of each muscle pair during the reaching phase (EMG_{RP}) were estimated by calculating the root mean square (RMS) of the EMG signals averaged from the right and left sides. The average of the RMS for the middle 1.5 s within the 3-s baseline EMG was calculated as the normalization reference ($EMG_{baseline}$). EMG_{RP} was normalized by $EMG_{baseline}$ for cross-muscle and cross-patient comparisons. Comparisons of the EMG baseline between the controls and patients were conducted before normalization to ensure an equal normalization reference between the two groups (see Supplementary material Methods S).

2.6. Statistical analysis

Demographic data of the controls and patients were compared using independent *t*-tests for the numerical data and using chi-square analysis for the nominal data. The VAS and ODI scores of the patient group between pre- and post-operation were examined using a Wilcoxon sign-rank test. Independent *t*-tests were performed to compare the differences in SLRT, back muscle strength, and reaching distance, between the control and patient groups. Paired *t*-tests were performed to compare the differences between pre- and post-operation with the patient group of the following variables: SLRT, back muscle strength, and reaching distance. Multivariate analyses of variance (MANOVAs) were performed to evaluate the muscle activities of the control group, and patient groups at pre- and post-operation, respectively. Follow-up univariate analysis was conducted to identify the main effects of each muscle pair. All statistical analyses were performed using SPSS (version 18.0), and the level of significance was set as $p < .05$.

The PCA was chosen as a dimension reduction procedure to identify the relevant muscles out of the 8 pairs of muscle recorded during the forward reaching movement (Hwang, Yang, Huang, & Guo, 2009; Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2004). The PCA was performed using the Machine Learning Toolbox (Jang, 2014). Specifically, the variability in muscle activation patterns during the forward reaching movement was examined with the PCA of the covariance matrix of the normalized RMS value for each muscle pair from all participants and trials for the controls as well as patients at pre- and post-operation (Krishnamoorthy et al., 2004). Data in the rows of the matrix were of Trials 1–5 of Participant 1, Trials 1–5 of Participant 2, and so on. The values in the columns of the matrix were RMS value of the 8 muscle pairs. For each condition (the controls as well as patients at pre- and post-operation), the obtained eigenvalues and principal components (PCs, i.e., eigenvectors) of the matrices were considered. The contribution of each muscle to every PC was evaluated to determine the significance (whether the muscle loading coefficient was greater than or equal to 0.5) (Krishnamoorthy et al., 2003). The following criteria were used to determine the number of the PCs to retain: (1) the PC accounting for more than 10% of the total variance, and (2) at least one muscle group that was loaded significantly (Danna-Dos-Santos, Slomka, Zatsiorsky, & Latash, 2007; Klous, Danna-dos-Santos, & Latash, 2010; Krishnamoorthy et al., 2003; Robert, Zatsiorsky, & Latash, 2008).

Because the first PC (PC1) account for the majority of the data variance, PC1 and its corresponding muscle loading coefficient for each condition were used to reflect the dominant movement pattern (i.e., the movement pattern most people adopted) with the associated muscle contributions during forward reaching movement. In addition, to evaluate the differences in variability explained by PC1 directly for each control and patient at pre- and post-operation, we conducted PCA by aggregating all of the participants and trials from both the controls and patients into a single matrix. The obtained PC1 and its obtained loading coefficients were evaluated to determine the dominant movement pattern. The data from each condition (i.e., control as well as patients at pre- and post-operation) were then projected onto the first principal axis to obtain the variance explained by PC1 for each condition. In addition, to further examine difference in the dominant movement pattern reflected in PC1 among the controls and patients at pre- and post-operation, the PC scores for each condition were extracted. Independent *t*-tests and paired *t*-test were performed respectively to compare difference in the PC scores between the controls and patients, and patients before and after surgery.

3. Results

3.1. Demographic data

Demographic data of the control and patient groups are shown in Table 1. Overall, no significant differences existed between both groups regarding age, sex, body height, and body weight. All patients underwent Mini-TLIF surgery using the same surgical procedure (Asgarzadie & Khoo, 2007) performed by a single orthopedic surgeon, and the operated levels ranged from L2 to S1.

3.2. Clinical evaluation

No significant differences in the SLRT of both legs were observed between the control (right/left: 72°/71°) group and the patient group (right/left: 72°/69°) (right: $t = 0.417$, $p = .679$; left: $t = 0.882$, $p = .384$). The patients showed significant improvements in pain intensity (VAS) and daily activity functioning (ODI). Their VAS values improved significantly (pre-operation vs. post-operation: 7 vs. 3, $z = -3.582$, $p < .001$), as did ODI score (42% vs. 22%, $z = -3.568$, $p < .001$). No difference in back muscle strength was observed between the pre-operation (23 kg) and post-operation (25 kg) measurements ($t = -1.541$, $p = .143$). Overall, the control group showed greater back muscle strength compared to that of the patient group at both pre-operation (58 kg vs. 23 kg, $t = 4.585$, $p < .001$) and post-operation (58 kg vs. 25 kg, $t = 3.897$, $p < .001$).

3.3. Forward reaching movement and muscle activities

Significant differences in the reaching distance were identified between the control and patient groups pre-operatively (97% (23 ± 4 cm) vs. 73% (18 ± 5 cm), $t = 3.922$, $p < .001$) and 1 month post-operatively (97% (23 ± 4 cm) vs. 70% (17 ± 6 cm), $t = 3.930$, $p < .001$). However, patients' reaching distance did not differ pre- and post-operation ($t = 0.943$, $p = .358$). The normalized RMS values of the EMG in the patient group were significantly smaller than the control group both pre-operatively (Wilk's Lambda = 0.601, $F_{(1,36)} = 2.573$, $p < .05$) and post-operatively (Wilk's Lambda = 0.629, $F_{(1,36)} = 2.285$, $p < .05$). The follow-up univariate analysis showed significant differences for the ES, MUL, and MEG muscles (all $p < .05$, Fig. 3). Overall, the patient group did not show significant improvement in the RMS values of the EMG for all 8 muscle pairs post-operatively (all $p > .05$, Fig. 3).

3.4. Muscle activation patterns

Based on the criteria mentioned in 2.6, the first four PCs were selected for the control group (PC1–PC4), and the first three PCs (PC1–PC3) were selected for the patients at both pre- and post-operation (Fig. 4A). The total variance explained by these selected PCs for the controls, as well as patients at pre- and post-operation were 81%, 84%, and 80%, respectively (Fig. 4B). Overall, the percentage of the variance explained by PC1 appeared to be greater for the patients (47% pre-operatively and 54% postoperatively) compared to those of the controls (36%).

Tables 2–4 showed the extracted PCs and their loading coefficients for the controls as well as patients at pre- and post-operation. The dominant muscle activation pattern, reflected in the individual loading of each muscle pair in PC1, differed between the controls and patients (Tables 2–4). Significant loading coefficients (>0.5) for the back muscles (ES and MUL) were exhibited in the controls, whereas the patient group exhibited significant loading coefficients for the leg muscles in TA and MEG pre-operatively and in TA and BF post-operatively (Tables 2–4). For the remainder of the PCs selected for each condition (PC2–PC4 for controls and PC2–PC3 for patients), significant loadings were found mostly on the leg muscles (RF, TA, MEG, and BF, Tables 2–4).

Fig. 5A showed the results for the percentages of the variance explained by each PC derived from a single matrix aggregating all of the participants and trials from the controls and patients (both Pre-op and Post-op). Overall, PC1 explained 40% of the dataset variance, with significant loading on MEG (Table 5). Fig. 5B showed the variances explained by the same set of PCs derived from a single matrix for each condition. Overall, the percentage of the variance explained by PC1 was the highest in patients at post-operation (49%). The percentage value for the controls and patients at pre-operation were 33% and 39%, respectively. In addition, the PC scores approached the borderline of significance between the controls and patients at pre-operation ($p = .08$), and were significantly different between the controls and patients at post-operation ($p < .05$). There was no difference in the PC scores between the patients at pre- and post-operation ($p = .358$).

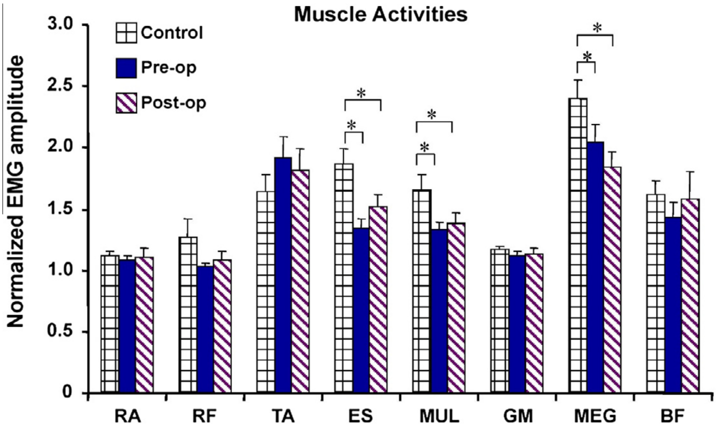

Fig. 3. Muscle activities during forward reaching for the control group and patient group at pre- and post-operation. Pre-op: patient group at pre-operation; Post-op: patient group at post-operation; RA: rectus abdominis, RF: rectus femoris, TA: tibialis anterior, ES: erector spinae, MUL: multifidus, GM: gluteus maximus, MEG: the medical head of the gastrocnemius, and BF: biceps femoris. Asterisks indicate $p < .05$.

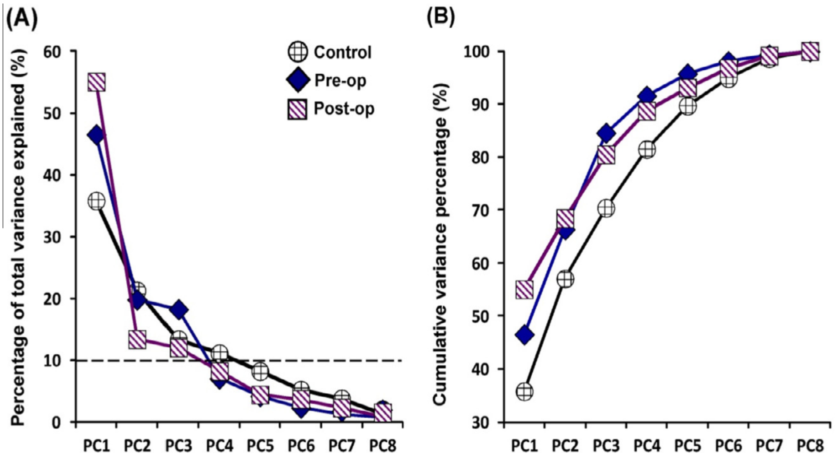

Fig. 4. (A) The percentages of variance accounted by each PC derived for control, and patients at pre-operation (Pre-op) and post-operation (Post-op). The horizontal line denotes 10% of the total variance. PC1 to PC8: the first to the eighth principal components. (B) the cumulative percentages of variance accounted by the PCs for the controls as well as patients at pre- and post-operation.

Table 2
The PCs extracted and their loading coefficients for the control group.

Muscle group	PC1	PC2	PC3	PC4
RA	0.0597	−0.0191	−0.0419	−0.1743
RF	−0.0583	0.2089	−**0.5694**	−**0.7701**
TA	0.1969	−0.0578	**0.7127**	−0.4850
ES	**0.5101**	−0.3271	0.0779	−0.2736
MUL	**0.5361**	−0.1334	−0.1467	0.0975
GM	0.0546	0.0627	−0.0155	0.0123
MEG	0.4489	**0.8623**	0.0729	0.1268
BF	0.4497	−0.2834	−0.3647	0.2017

Note: Significant loading (⩾0.5) was shown in bold. RA: rectus abdominis, RF: rectus femoris, TA: tibialis anterior, ES: erector spinae, MUL: multifidus, GM: gluteus maximus, MEG: the medical head of the gastrocnemius, and BF: biceps femoris.

Table 3
The PCs extracted and their loading coefficients for patients at pre-operation.

Muscle group	PC1	PC2	PC3
RA	−0.0120	−0.0252	−0.0194
RF	−0.0008	0.0294	−0.0186
TA	**0.6219**	**0.6770**	0.3235
ES	0.2352	0.0173	−0.0400
MUL	0.1833	0.0432	−0.0034
GM	0.0690	0.0335	−0.0309
MEG	**0.7141**	−**0.6549**	−0.1374
BF	0.0976	0.3286	−**0.9344**

Note: Significant loading (⩾0.5) was shown in bold.

4. Discussion

In this study, we examined the pain intensity, daily activity functioning, and muscle activation patterns of healthy controls and LBP patients before and after minimally invasive lumbar spinal fusion. The patient group showed significant improvements in pain intensity and daily activities at 1 month

Table 4
The PCs extracted and their loading coefficients for patients at post-operation.

Muscle group	PC1	PC2	PC3
RA	0.0345	0.1214	−0.0500
RF	0.0642	−0.0507	−0.1114
TA	**0.6243**	**0.7398**	−0.0341
ES	0.3759	−0.1291	−0.0714
MUL	0.2473	−0.0364	0.0209
GM	0.1554	−0.2148	0.0756
MEG	0.2579	−0.1864	**0.9207**
BF	**0.5583**	**−0.5800**	−0.3535

Note: Significant loading (⩾0.5) was shown in bold.

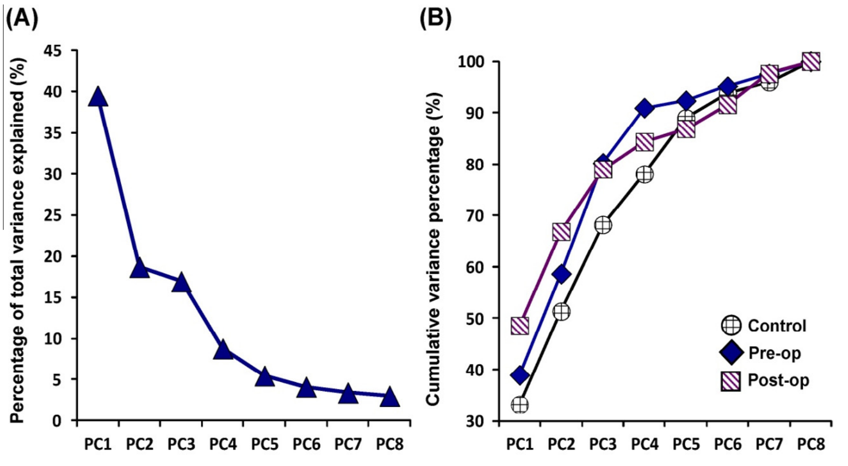

Fig. 5. (A) The percentages of variance accounted by each PC derived from a single matrix combining all participants and trials from both controls and patients. (B) The cumulative percentages of variance accounted by the PCs for the controls as well as patients at pre- and post-operation.

Table 5
PC1 and its loading coefficients derived from a single matrix combining all participants and trials from both controls and patients.

Muscle group	PC1
RA	0.0366
RF	0.0381
TA	0.4641
ES	0.4202
MUL	0.3411
GM	0.1027
MEG	**0.5505**
BF	0.4188

Note: Significant loading (⩾0.5) was shown in bold.

after surgery. However, they also exhibited decreased muscle activities and reaching distances, and altered muscle coordination patterns during forward reaching movement compared with those of the healthy controls. During the forward reaching movement, the patients tended to use a muscle strategy that relied more on leg muscles and less on lumbar extensor muscles; which may indicate that a muscle activation pattern is employed to compensate for the insufficient function of the paraspinal muscles.

4.1. Improvements in pain severity and daily activity functioning at one month after surgery

Lumbar fusion has been found to be effective for improving LBP symptoms in some individuals with common spinal disorders, such as degenerative disc disease and spondylolisthesis (Carreon et al., 2008; Phillips et al., 2013). Specifically, minimally invasive fusion surgery can reduce the extent of the damage of the paraspinal muscles, and hence decrease postoperative pain and recovery time. Similar to previous findings (Anand, Baron, & Bray, 2007; Pao, Chen, & Chen, 2009; Rodriguez-Vela et al., 2009), the patients in this study showed a noticeable improvements just 1 month after surgery, as evidenced by significant changes in their pain intensity and daily activity functioning. However, compared with the controls the patients had a shorter reaching distance and lower muscle activities at both pre-operative and post-operative evaluations, which may indicate deficiencies in the neuromuscular function.

4.2. Deficiencies in neuromuscular control sustained following spinal surgery

Forward reaching movement is a functional activity frequently performed in daily routine tasks. As forward bending progresses, the flexion moment of the trunk increases and places tensile stress on the back, which must be properly balanced by back muscles and ligaments (Farfan, 1975). Electromyographic study has shown that the activities of the erector spinae increased as the forward bending movement increased (Carlsöö, 1961). Given the substantial involvement of the back muscles, forward reaching movement is considered challenging for patients with LBP after fusion surgery, and could be used as an index to evaluate post-operation recovery.

The patients in this study exhibited significantly shorter reaching distances than those of the controls, and they did not show improvements 1 month after surgery despite their reduced pain severity. Because hamstring flexibility did not differ between the controls and patients, the decline in reaching performance can be reasonably attributed to other factors. One explanation may be that the patients adopted a more conservative approach after surgery, especially because they were instructed to protect their spine for at least 3 months by wearing a lumbo-sacral orthosis. In addition, the decline may be attributed to an overall decrease in neuromuscular control, as evidenced by the reduced back muscle strength and lower muscle activities of the paraspinal and leg muscles (Fig. 3). These results support previous findings that weaker back muscle strength (Kramer et al., 2001) and changes in muscle activity, such as a delayed firing time and abnormal patterns, were experienced after spinal surgery (Ahern, Follick, Council, Laser-Wolston, & Litchman, 1988; Arendt-Nielsen, Graven-Nielsen, Svarrer, & Svensson, 1995; Radebold, Cholewicki, Polzhofer, & Greene, 2001). Although one may argue that differences in muscle activities between the controls and patients were caused by different reaching distances, we conducted additional analysis by comparing the muscle activities between the controls and patients at a fixed distance to rule out such a possibility (see Supplementary material Discussion S).

It should be noted that fear of pain and subsequent avoidance behaviors may also be relevant to patients' declined performance, and should not be underestimated (Fritz, George, & Delitto, 2001; George, 2006; Vlaeyen & Linton, 2000). Elevated fear-avoidance beliefs have been shown to associate with physical impairment in both chronic (Al-Obaidi, Nelson, Al-Awadhi, & Al-Shuwaie, 2000; Geisser, Haig, Wallbom, & Wiggert, 2004) and acute LBP patients (George, Fritz, & McNeil, 2006). For example, fear-avoidance beliefs were significantly correlated with reduced lumbar flexion range and lumbar extensor strength in patients with chronic LBP (Al-Obaidi et al., 2000; Geisser et al., 2004). Further research on fear-avoidance after fusion surgery needs to be conducted to elucidate the relationship between the fear-avoidance behavior and the neuromuscular control.

4.3. Compensatory muscle activation patterns during forward reaching movement sustained after spinal surgery

During a forward reaching movement, back muscles have to contract to overcome the gravitational force acting on the trunk (Carlsöö, 1961). Because of the reduced back muscle function observed in the patient group, we expected an altered muscle coordination pattern would be observed in the patient group to overcome the insufficient paraspinal muscles function. We performed the PCA to explore this possibility. Consistent with our hypothesis, the PCA results showed differences in the way patients performed the forward reaching movement compared to that of the healthy controls, especially in their dominant movement pattern reflected in PC1. Firstly, significant loadings only on leg muscles were found in all the PCs extracted for patients at both pre- and post-operation (PC2–PC3 in Tables 3 and 4); however, such findings were only true for the PCs extracted other than PC1 for the control group (PC2–PC4 in Table 2). In addition, unlike the controls who showed significant loading coefficients on the back muscles (ES and MUL) in their dominant pattern (PC1), the patients showed significant loading coefficients on their leg muscles (TA, MEG, and BF) (Tables 2–4). Further, by combining the controls and patients together, a movement pattern with leg muscle significantly loaded could explain greater variance for the patients than for the controls (Fig. 5B), and such differences were further supported by difference in the PC scores between the controls and patients. Taken together, these findings suggested that patients may attempt to compensate for their insufficient paraspinal function by predominantly relying on their leg muscles to perform forward reaching movement.

Moreover, such a compensatory muscle activation pattern could be explained by patients' habitual protective behavior. It has been shown that the presence of pain could cause imbalance muscle activation during symmetrical trunk extension movement in LBP (Oddsson & De Luca, 2003). Induced pain has been shown to produce kinematic changes in trunk forward bending movements including a reduction in the velocity and range of motion (Zedka, Prochazka, Knight, Gillard, & Gauthier, 1999). Although pain has been proposed as a factor to kinematic alterations in people with LBP, the causative mechanisms were still not well understood (Williams, Haq, & Lee, 2010). Because the patients demonstrated substantially decreased pain intensity at 1-month post-operation, the continued leg-dominant activation pattern from pre- to post-operation the patients exhibited may suggest the possibility of a habitual psychological protective strategy they adopted, potentially driven by pain, which would be an interesting topic for further exploration.

It is interesting to note that although in general the patients and controls had similar relative muscle activities among the 8 pairs of muscles (Fig. 3), they differed in their control of those muscles while performing forward reaching. Such a change in the control strategy was often not detectable by simple comparison of the EMG amplitudes between groups. Considering the declined back and leg muscle activities in patients, one may easily conclude that the patients unlikely depend on those muscles when performing the forward reaching movement. In fact, the PCA results revealed that patients might still rely chiefly on their leg muscles to perform the forward reaching movement even with their declined leg muscle activities. Multiple-muscle activation pattern may not be identified using traditional EMG amplitude comparison, unless using factor analysis like PCA. In addition, such a leg dominant activation pattern in the patient group became more consistent, as indicated in the increase in the variance explained by PC1 observed post-operatively (Figs. 4A and 5B). In other words, the patients seemed to be less flexible than the controls in control of the reaching movement. Previous studies have shown that variability reflects flexible control of a motor task and might be a crucial feature in adaptive control systems (Hsu, 2014; Hsu, Chou, & Woollacott, 2013; Hsu, Lin, Yang, & Cheng, 2014; Hsu & Scholz, 2012).

The compensatory muscle coordination pattern (i.e., the leg-dominant strategy) observed in the patients after spinal fusion surgery could also be explained from a balance control perspective (Pao, Yang, Hsiao, et al., 2014). A forward reaching movement can be performed using combinations of the lumbar, pelvis, hip, and ankle joints (Cavanaugh et al., 1999; Lin & Liao, 2011). Healthy young adults reached with greater trunk flexion and less lower limb flexion compared to that of the older adults during the functional reach test (Cavanaugh et al., 1999). In addition, the older adults were found to primarily adopt a hip strategy instead of an ankle strategy, to maintain their center of mass near the base of support when reaching forward (Lin & Liao, 2011). Although the patients in this study consistently used leg-dominant activation pattern to perform forward reaching movement, a change in the significant muscle loading coefficients from MEG at pre-operation to BF at post-operation could imply an adjustment in the strategy adopted (i.e., from an ankle to a hip strategy). Similar to previous findings (Lin & Liao, 2011), such an adjustment can enable patients to maintain their center of mass near the base of the support and ensure a safe transfer of their body during the movement in a condition of declined neuromuscular function.

4.4. Limitations of the study

Although minimally invasive procedure could allow for early evaluation of patients' neuromuscular control ability, 1-month post-operative evaluation adopted in the current study may be insufficient for healing of the paraspinal muscles and adjacent tissues. A long-term follow-up would be necessary to monitor the progress of the patients' neuromuscular control ability after the minimally invasive lumbar spinal fusion.

4.5. Clinical relevance

The patients' pain severity and daily activity functioning improved at 1 month after the minimally invasive lumbar spinal fusion; however, they still showed deficiencies in their neuromuscular control. On the other hand, they developed a compensatory movement pattern to overcome the insufficient back muscle function which may lead to a more serious secondary pathology in the future. Paraspinal muscle damage caused by surgery has been found to accelerate muscle atrophy and fatty infiltrations (Fan et al., 2010). Therefore, whether minimally invasive lumbar fusion surgery will cause the same paraspinal muscle atrophy and fatty infiltration in the long-term, and how patients' declined neuromuscular control will correlate to the morphology changes in paraspinal muscles should be further monitored by magnetic resonance imaging (MRI) records in future research. Nevertheless, early intervention focusing on training paraspinal muscles should be considered for patients who have undergone lumbar spinal fusion to prevent potential degeneration of the paraspinal muscles and to increase spinal stability.

5. Conclusion

The patients after minimally invasive lumbar spinal fusion showed substantial improvement in pain severity and daily activity functioning at 1 month after surgery, but exhibited declined muscle activities and altered muscle coordination patterns during forward reaching. The patients might have adopted a leg-dominant strategy to compensate for their insufficient paraspinal muscle function. Therefore, early rehabilitation focusing on motor control training should be considered for patients who have undergone lumbar spinal fusion.

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Conflict of Interest

All coauthors have no financial disclosure and conflict of interest to report.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2015.01.002.

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