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ORIGINAL ARTICLE

Correlation between osteoporotic vertebral fracture and abdominal trunk muscle strength in middle-aged and older women

Satoshi Kato[1] · Satoru Demura[1] · Yuki Kurokawa[1] · Kazuya Shinmura[1] · Noriaki Yokogawa[1] · Noritaka Yonezawa[1] · Takaki Shimizu[1] · Norihiro Oku[1] · Ryo Kitagawa[1] · Hidenori Matsubara[1] · Tamon Kabata[1] · Hiroyuki Tsuchiya

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Abstract

Summary We investigated the correlation between abdominal trunk muscle strength and spinal deformities in middle-aged and older women. The results indicated that abdominal trunk muscle weakness, older age, and low lumbar bone mineral density were significant risk factors associated with the presence of OVFs in the lower thoracic and lumbar spine.

Purpose We developed an innovative exercise device for the abdominal trunk muscles that also measures muscle strength. We investigated the correlation between the strength and thoracolumbar spinal deformity in middle-aged and older women.

Methods This study included 206 consecutive female patients who were 50 years or older and scheduled to undergo surgery for degenerative diseases of the lower extremities. Patients with a history of symptomatic osteoporotic vertebral fractures (OVFs) requiring treatments were excluded. Before surgery, patients underwent physical measurements including abdominal trunk muscle strength using our device, full-spine standing radiography, and bone mineral density measurement of the lumbar spine (L-BMD). According to radiographic findings of the radiogram, patients were divided into four groups: control group ($n = 134$), listhesis group ($n = 29$), scoliosis group ($n = 19$), and fracture group ($n = 24$). The Tukey-Kramer honestly significant difference test was used to compare all measurements among the four groups. To identify factors associated with the presence of OVFs, a multivariate logistic regression analysis was performed.

Results The average abdominal trunk muscle strength in the fracture group was significantly lower than that of the control group. The multivariate analysis revealed that abdominal trunk muscle weakness, older age, and a low L-BMD were associated with OVF findings.

Conclusions Abdominal trunk muscle weakness in middle-aged and older women was associated with OVF. The strength measurement can be a risk assessment of OVF.

Keywords Abdominal trunk muscle strength · Elderly women · Innovative exercise device · Muscle weakness · Osteoporotic vertebral fracture · Spinal deformity

Introduction

The increasing incidence of osteoporosis-associated fractures is a major socioeconomic and medical problem in developed countries owing to the increasing older population [1]. Osteoporotic vertebral fracture (OVF) is the most common type of fracture in older adults [2] and has been described as the hallmark of osteoporosis [3]. Fracture prevalence and incidence increase with age, and low bone mineral density (BMD) is predictive of OVF in both men and women [4]. However, the events and circumstances leading to OVF are frequently unclear. In two previous studies examining the circumstances surrounding clinically diagnosed OVFs, about 47% of fractures occurred "spontaneously" or in otherwise unknown circumstances [5, 6]. Taken together, these observations suggest that there are important but poorly understood factors other than BMD that increase the OVF risk in some individuals.

Neuromuscular changes with aging are well documented. These include both loss of lean muscle mass or sarcopenia and

✉ Satoshi Kato
skato323@gmail.com

[1] Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kanazawa University, 13-1 Takara-machi, Kanazawa 920-8641, Japan

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decline in muscle function, which is sometimes referred to as dynapenia [7]. Importantly, loss of muscle strength with aging occurs twofold to fivefold faster than loss of muscle size [8], at least in the lower limb. Although not as widely studied as the lower limb muscles, the trunk musculature also exhibits age-related decline. For example, older adults have decreased lumbar extensor strength [9] and increased fatty infiltration of the trunk musculature [10] compared with young adults. Older adults also have higher levels of trunk muscle activation compared with young adults in both agonist and antagonist muscles, indicating that aging affects the neuromuscular control of the trunk [11]. Moreover, a recent review of in vivo and computational modeling studies highlighted the importance of understanding spinal loading to better prevent and manage spinal disorders [12]. As significant uncertainties exist regarding the causes of OVFs, it seems plausible that neuromuscular function of the trunk muscles could play an important role in the etiology.

We have developed an innovative exercise device for the abdominal trunk muscles (Nippon Sigmax Co., Ltd., Shinjuku-ku, Tokyo, Japan) [13]. This device enables patients to perform strengthening exercises for the abdominal trunk muscles in a sitting position without the need for trunk movement. Therefore, these exercises are more easily accessible to patients with loss of flexibility, spinal deformity, or severe back pain, such as older patients with OVF. The device also contains a built-in system for measuring abdominal trunk muscle strength, thus reinforcing adherence to the exercise program. Our previous study demonstrated that the device showed excellent reliability and accuracy to measure abdominal trunk muscle strength and that the strengthening exercises using the device both activate and increase the strength of the diaphragm, abdominals, and pelvic-floor muscles [14].

In this study, we investigated the correlation between abdominal trunk muscle strength in middle-aged and older women, measured using this device, and spinal deformity in the lower thoracic or lumbar regions including OVF.

Methods

Description of the device

As previously described in detail [13], the device has a similar design to that of a sphygmomanometer, with an inflatable cuff and mechanical manometer to measure pressure. To obtain a measurement in the sitting position, the cuff is placed around the subject's abdomen and is inflated, applying adequate pressure (baseline pressure) to the abdominal wall. Under the baseline pressure, the subject exerts the maximum force by contracting the abdominal muscles, and the pressure in the cuff is elevated until it reaches a peak (peak pressure). The mechanical manometer calculates and reports the pressure value by subtracting the baseline pressure from the peak pressure to provide the muscle strength value. In this study, the muscle strength value was used to define abdominal trunk muscle strength.

During muscle strengthening exercises using the device, the subject contracts the abdominal wall muscles intermittently or continually under pressure from the cuff. This exercise is similar to a bracing exercise, which functions as a stabilization exercise [15]. However, the exercise is performed under pressure from the cuff, which allows the subjects to easily and powerfully contract the abdominal trunk muscles.

Participants

Clinical data of 324 patients, who were scheduled to undergo surgery for degenerative diseases of the lower extremities at our hospital and who agreed to participate in the following preoperative examination, were prospectively collected from January 2016 to December 2018. Before surgery, patients underwent physical measurements, full-spine standing radiography, and BMD measurement of the lumbar spine (L-BMD). Locomotive syndrome, which is defined as a condition of reduced mobility due to impairment of a locomotive organ, was assessed using the 25-question Geriatric Locomotive Function Scale (GLFS-25) in each patient [16]. Patients who were male and/or younger than 50 years were excluded from analysis because the majority of patients in the cohort were female, spinal deformities including OVF often appeared in women 50 years or older, and muscle strength was different between men and women. Patients with previous spine surgery or a history of symptomatic OVF and respective treatment including rest and spinal orthosis were also excluded from the study. Finally, a total of 206 consecutive female patients 50 years or older were evaluated in the study (Table 1).

Evaluation

We obtained anthropometric measurements including body height, body weight, and body mass index. We measured each patient's grip strength using a grip dynamometer (TTM Dynamometer; Tsutsumi, Tokyo, Japan) and abdominal trunk muscle strength using our device. We also obtained each patient's five-point numerical rating scale (NRS) score for back pain (0 = no pain to 4 = severe pain) from the result of question 2 of the GLFS-25 [16].

According to radiographic findings (Fig. 1), patients were divided into four groups: control group ($n = 134$), which includes patients without specific findings; listhesis group ($n = 29$), which includes patients with degenerative spondylolisthesis in the lumbar spine in the sagittal plane; scoliosis group ($n = 19$), which includes patients with

Table 1 Subject characteristics and inclusion/exclusion criteria of the study

Subject characteristics	
No. of subjects	206
Age (years), mean ± SD [range]	66.7 ± 8.1 [50–84]
Height (cm), mean ± SD [range]	152.4 ± 6.0 [130–168]
Weight (kg), mean ± SD [range]	55.5 ± 9.6 [31.6–84.1]
BMI (kg/cm^2), mean ± SD [range]	23.9 ± 4.1 [14.1–36.7]
Grip strength (kg), mean ± SD [range]	20.4 ± 5.9 [4–34]
ATM strength (kPa), mean ± SD [range]	5.2 ± 2.9 [0.4–13.4]
GLFS-25 score (point), mean ± SD [range]	39.9 ± 21.2 [4–97]
NRS (0–4) of back pain (point), mean ± SD [range]	1.3 ± 1.1 [0–4]
L-BMD (g/cm^2), mean ± SD [range]	1.05 ± 0.21 [0.63–1.80]
LL (degree), mean ± SD [range]	44.9 ± 17.8 [−6.0–80]
PO (degree), mean ± SD [range]	2.2 ± 2.1 [0–10]
Inclusion criteria of the study	
· They underwent surgeries for degenerative diseases of the lower extremities in our hospital from January 2016 to December 2018. · They agreed to participate in the preoperative examination.	
Exclusion criteria	
· They were male and/or < 50 years of age. · They had an experience of spine surgery or symptomatic OVF requiring treatments before the examination.	

ATM abdominal trunk muscle; BMI body mass index, *GLFS-25* 25-Question Geriatric Locomotive Function Scale, *NRS* numerical rating scale, *L-BMD* bone mineral density of the lumbar spine, *LL* lumbar lordosis, *OVF* osteoporotic vertebral fracture, *PO* pelvic obliquity, *SD* standard deviation

degenerative scoliosis in the lumbar spine; fracture group (n = 24) which includes patients with OVF in the lower thoracic or lumbar spine. Spondylolisthesis was defined as anterior slip of the upper vertebra ≥ 5%. Scoliosis was defined as a Cobb angle > 20°. OVF was defined as a grade 1 to 3 fracture according to the Genant semiquantitative method [17]. When patients had spondylolisthesis and/or scoliosis as well as OVF, they were included in the fracture group. When patients had spondylolisthesis and scoliosis, they were included in the scoliosis group.

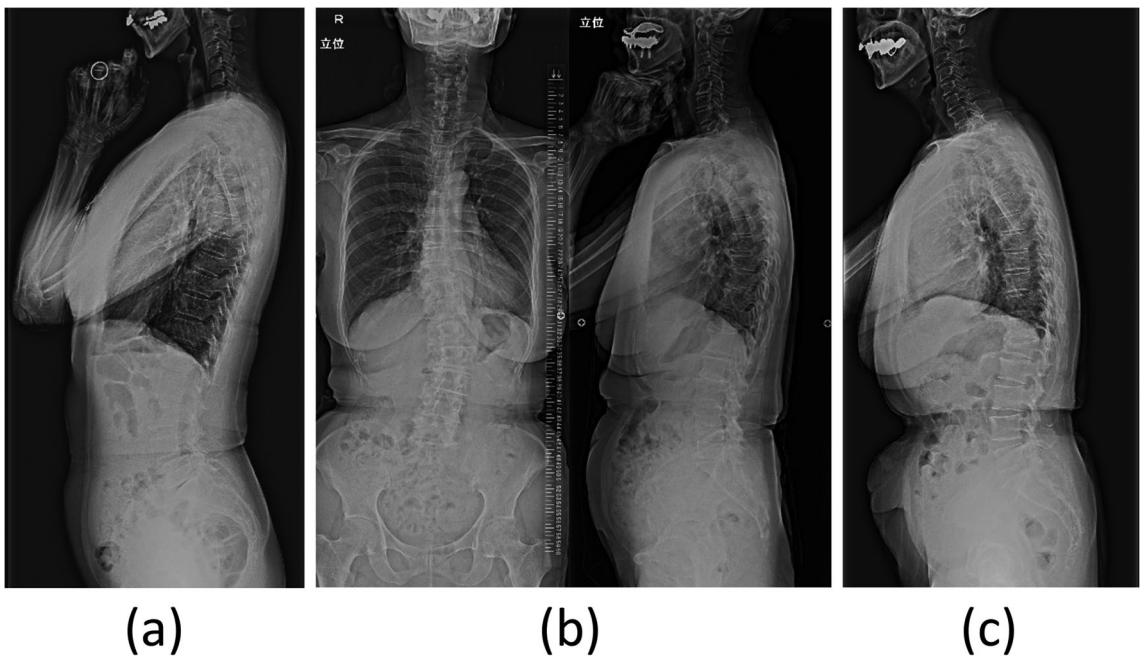

Fig. 1 Spinal deformities identified on full-spine standing radiography. **a** Degenerative spondylolisthesis at L4 (Meyerding grade 2). **b** Degenerative scoliosis of 25° from T12 to L3. **c** Osteoporotic vertebral fracture at L1 (Genant grade 2)

Clinical factors compared among the four groups included age, height, weight, body mass index, grip strength, abdominal trunk muscle strength, GLFS-25 score, NRS score for back pain, L-BMD, and radiographic parameters, including lumbar lordosis in the sagittal plane and horizontal pelvic obliquity in the coronal plane. These factors were also evaluated as predictive variables for presence of OVF in the lower thoracic or lumbar spine. The clinical factors and radiographic findings were also evaluated for their effect on abdominal trunk muscle strength measured using the device.

Statistical analysis

All data are presented as mean and standard deviation. Differences in continuous variables between the two groups were examined using the Student *t* test for parametric data and the Mann-Whitney *U* test for nonparametric data. Comparison of continuous variables among the four groups was conducted using the Tukey-Kramer honestly significant difference test. To identify factors associated with presence of OVF in the lower thoracic or lumbar spine, a multiple logistic regression model was used to obtain adjusted odds ratios (aORs) with 95% confidence intervals (CIs). Multiple regression analysis was also performed to identify factors that affect abdominal trunk muscle strength. SPSS version 19.0 for Windows (IBM Corp., Armonk, NY, USA) was used for all statistical analyses, with the level of statistical significance set at 0.05.

Results

Table 2 shows the distribution of the clinical parameters among the four groups. The fracture group was significantly older with lower abdominal trunk muscle strength compared with the control group. The average abdominal trunk muscle strength was 5.5 kPa in the control group, 5.3 kPa in the listhesis group, 4.4 kPa in the scoliosis group, and 3.5 kPa in the fracture group. The scoliosis group was significantly older and shorter in height compared with the control group. The average lumbar lordosis in the scoliosis group was smaller than that in the other three groups.

Among the 24 patients in the fracture group, 20 had a single OVF (T8 in 4 patients, T9 in 1, T10 in 1, T11 in 1, T12 in 6, L1 in 3, L3 in 2, and L4 in 2), whereas the other four had multiple OVFs. The patients in the fracture group had no history of symptomatic disease requiring specific treatment. Twelve (50%) of the 24 patients received pharmacologic treatment for osteoporosis.

When the patients were divided into two groups based on the presence of OVF in the lower thoracic or lumbar spine as the OVF group (fracture group, $n = 24$) and the non-OVF group (other three groups, $n = 182$), the OVF group was significantly older with lower abdominal trunk muscle strength compared with the non-OVF group according to univariate analyses (Table 3). In addition, the average L-BMD in the OVF group was lower than that in the non-OVF group.

In the multiple logistic regression analysis, abdominal trunk muscle weakness (Exp(B) = 0.750; CI, 0.608–0.924; $P = 0.007$), older age (Exp(B) = 1.093; CI, 1.023–1.168; $P = 0.009$), and low L-BMD (Exp(B) = 0.078; CI, 0.006–0.943; $P = 0.045$) were significant risk factors for OVF in the lower thoracic or lumbar spine (Table 4). In addition, the presence of OVF and GLFS-25 score were independently associated with abdominal trunk muscle strength measured using the device, whereas age, body mass index, and other spinal parameters, including lumbar lordosis and presence of scoliosis, did not affect the strength (Table 5).

Discussion

This study investigated the correlation between abdominal trunk muscle strength, measured using our device, and spinal

Table 2 Clinical data of the four groups

	Control ($n = 134$)	Listhesis ($n = 29$)	Scoliosis ($n = 19$)	Fracture ($n = 24$)
Age (year)	64.9 ± 7.7	68.0 ± 8.6	71.0 ± 5.5*	71.8 ± 8.1*
Height (cm)	153.5 ± 5.6	150.7 ± 5.9	149.2 ± 6.3*	151.0 ± 7.1
Weight (kg)	56.3 ± 9.9	53.7 ± 9.3	54.4 ± 7.8	54.2 ± 9.7
BMI (kg/m^2)	23.9 ± 4.2	23.7 ± 4.4	24.5 ± 3.4	23.8 ± 3.9
Grip strength (kg)	21.3 ± 5.9	19.1 ± 5.1	19.2 ± 6.6	18.3 ± 5.8
ATM strength (kPa)	5.5 ± 3.0	5.3 ± 3.1	4.4 ± 2.6	3.5 ± 2.2*
GLFS-25 score (point)	38.5 ± 20.6	41.5 ± 21.0	44.9 ± 21.2	42.0 ± 25.4
NRS (0–4) of back pain (point)	1.2 ± 1.1	1.3 ± 1.1	1.8 ± 1.3	1.1 ± 1.0
L-BMD (g/cm^2)	1.058 ± 0.207	1.060 ± 0.243	1.110 ± 0.194	0.955 ± 0.203
LL (degree)	47.3 ± 16.2	47.4 ± 14.4	28.2 ± 19.7 #	41.9 ± 21.2
PO (degree)	2.1 ± 2.0	2.3 ± 2.5	2.3 ± 2.3	2.4 ± 2.1

ATM abdominal trunk muscle, *BMI* body mass index, *GLFS-25* 25-Question Geriatric Locomotive Function Scale, *NRS* numerical rating scale, *L-BMD* bone mineral density of the lumbar spine, *LL* lumbar lordosis, *PO* pelvic obliquity

*$P < 0.05$ versus normal group; #$P < 0.05$ versus normal, listhesis, and fracture group

Table 3 Difference of characteristics between patients with and without OVFs

	OVF ($n = 24$)	Non-OVF ($n = 182$)	P value
Age (year)	71.8 ± 8.1	66.0 ± 7.9	0.001
Height (cm)	151.0 ± 7.1	152.6 ± 5.9	0.220
Weight (kg)	54.2 ± 9.7	55.6 ± 9.6	0.476
BMI (kg/m^2)	23.8 ± 3.9	23.9 ± 4.2	0.862
Grip strength (kg)	18.3 ± 5.8	20.7 ± 5.9	0.058
ATM strength (kPa)	3.5 ± 2.2	5.4 ± 3.0	0.001
GLFS-25 score (point)	42.0 ± 25.4	39.7 ± 20.7	0.607
NRS (0–4) of back pain (point)	1.1 ± 1.0	1.3 ± 1.1	0.431
L-BMD (g/cm^2)	0.955 ± 0.203	1.063 ± 0.211	0.019
LL (degree)	41.9 ± 21.2	45.3 ± 17.3	0.376
PO (degree)	2.4 ± 2.1	2.1 ± 2.1	0.562

ATM abdominal trunk muscle, *BMI* body mass index, *GLFS-25* 25-Question Geriatric Locomotive Function Scale, *NRS* numerical rating scale, *L-BMD* bone mineral density of the lumbar spine, *LL* lumbar lordosis, *OVF* osteoporotic vertebral fracture, *PO* pelvic obliquity

deformity in the lower thoracic or lumbar regions including OVF, in middle-aged and older women, and the results indicated that abdominal trunk muscle strength in patients with OVF was significantly lower than that in patients without specific findings. Meanwhile, abdominal trunk muscle strength in patients with degenerative spondylolisthesis and/or scoliosis in the lumbar spine was not lower compared with patients without specific findings. In the multivariate analysis, abdominal trunk muscle weakness, older age, and low L-BMD were associated with the presence of OVF. Older age and low BMD are well-known predictors of OVF [4]. However, the present study is the first to focus on the effect of abdominal trunk muscle strength on spinal deformity in middle-aged and older women and to report the abdominal trunk muscle weakness as a novel risk factor for OVF. A history of symptomatic OVF and respective treatment, including rest and spinal orthosis, can influence the abdominal trunk muscle weakness. Therefore, patients with a history of symptomatic OVF were excluded from the study. The mean NRS scores for back pain in all four groups were equivalent (Table 2). These results indicate that the abdominal trunk muscle weakness is a significant risk factor for OVF.

Table 4 Multivariate analysis of associated factors for presence of OVF in the lower thoracic or lumbar spine

	aOR	P value	95% CI
Age, 1-year increase	1.093	0.009	1.023–1.168
Grip strength (kg), 1-unit increase	1.027	0.547	0.941–1.121
ATM strength (kPa), 1-unit increase	0.750	0.007	0.608–0.924
L-BMD (g/cm^2), 1-unit increase	0.078	0.045	0.006–0.943

aOR adjusted odds ratio, *ATM* abdominal trunk muscle, *CI* confidence interval, *L-BMD* bone mineral density of the lumbar spine, *OVF* osteoporotic vertebral fracture

A previous study demonstrated that muscle strength, measured using our exercise device, was correlated with the trunk flexor strength, including the abdominal rectus and oblique muscles located in the anterolateral aspect of the abdomen [13]. The diaphragm, abdominal rectus, external and internal oblique, transverse abdominal, and levator ani muscles were significantly activated while exercising using the device [14]. The abdominal core can be described as a muscular box with the abdominals in the front and sides, the paraspinals in the back, the diaphragm as the roof, and the pelvic floor as the base [18]. Contraction of the diaphragm increases the intra-abdominal pressure, thus contributing to spinal stability [18]. The strength of the abdominal trunk muscles, as measured using the device, is created by the contraction of all deep and superficial abdominal core muscles to increase intra-abdominal pressure, thus creating a semirigid cylinder surrounding the spinal column, which is capable of relieving some of the imposed stress on the vertebral column. In the

Table 5 Stepwise multiple liner regression analysis for abdominal trunk muscle strength measured using the device in the study population

	β	P value	VIF
Age (year)	− 0.029	0.675	1.092
BMI (kg/m^2)	0.001	0.985	1.018
GLFS-25 score (point)	− 0.030	0.002	1.001
L-BMD (g/cm^2)	− 0.034	0.614	1.032
LL (degree)	− 0.040	0.564	1.069
PO (degree)	− 0.037	0.587	1.003
Presence of OVF	− 1.784	0.004	1.001
Presence of lumbar scoliosis	− 0.090	0.185	1.020

BMI body mass index, *GLFS-25* 25-Question Geriatric Locomotive Function Scale, *L-BMD* bone mineral density of the lumbar spine, *LL* lumbar lordosis, *OVF* osteoporotic vertebral fracture, *PO* pelvic obliquity, *VIF* variance inflation factor

literature, an association between the abdominal core muscle weakness and the OVF risk has not been clearly documented. The impact of research on core stability exercises has been weakened by the lack of consensus on how to measure the core strength [19]. If core instability and weakness could be measured easily and reliably, clinical outcomes could be determined and proper emphasis could be placed on core strengthening of certain individuals. This device may be a viable option for measuring core muscle strength and has the potential to evaluate core stability. Thus, strength measurement using the device may also be used to assess the risk of OVF.

In the literature, back extensor strength has been shown to be an important factor in middle-aged and older women [20–22]. Sinaki et al. [23] showed that healthy, postmenopausal women who engaged in back extensor-strengthening exercises had a lower incidence of OVF. Another study demonstrated a significantly higher number of OVFs in patients with postmenopausal osteoporosis who followed a trunk flexion exercise program compared with those using a trunk extension exercise program [24]. They concluded that extension or isometric exercises are appropriate for middle-aged and older women who may have osteoporosis [24, 25]. In strength measurements or strengthening exercises using our device, the trunk flexor muscles including the abdominal rectus and oblique are mainly activated. However, the subjects are able to contract the abdominal trunk muscles in a sitting position without the need of movement of the trunk. Such isometric exercise does not impose a strain on the spine or extremities and may thus be appropriate for older patients and those with postmenopausal osteoporosis.

There is the possibility that the spinal deformity or back pain affects the intensity of abdominal muscle strength measured using the device. The mean lumbar lordosis in the scoliosis group was smaller than that in the other three groups; however, the multiple regression analysis revealed that the spinal parameters, including lumbar lordosis and presence of scoliosis, did not affect abdominal muscle strength. We suppose that the effect of the spinal deformity on muscle strength was limited because the measurement was obtained with isometric contraction in a sitting position. In addition, the mean NRS score for back pain was equivalent between the fracture group and the other groups. One of the advantages of our device is that there is no induction of back pain during strength measurement. In fact, no patient reported back or abdominal pain during measurement in this study.

The limitations of the present study include the cohort, which included patients with degenerative disease of the lower extremities, and the cross-sectional manner of data collection, which may have affected the results. Another study with a longitudinal design is required to confirm abdominal muscle weakness measured using the device as a risk factor for OVF. Further studies are also required to examine whether abdominal trunk muscle strengthening exercise lowers the incidence of OVF. Furthermore, back extensor muscle strength was not measured in this study; its correlation with abdominal trunk muscle strength and spinal deformity including OVF was not determined.

Conclusions

This study evaluated the abdominal trunk muscle strength measured using our device in 206 middle-aged and older women with and without spinal deformity including OVF, degenerative spondylolisthesis, and scoliosis. The results indicated that muscle strength is significantly lower in patients with OVF compared with patients without specific findings. In the multivariate analysis, abdominal trunk muscle weakness, older age, and low L-BMD were significant risk factors associated with the presence of OVF in the lower thoracic or lumbar spine.

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Compliance with ethical standards

Conflict of interest Nippon Sigmax Co., Ltd. provided the exercise device used in this study. The company did not have any control over the content of this article or the decision to approve or submit the manuscript for publication.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Cummings SR, Melton LJ (2002) Epidemiology and outcomes of osteoporotic fractures. Lancet 359:1761–1767
2. Burge R, Dawson-Hughes B, Solomon DH, Wong JB, King A, Tosteson A (2007) Incidence and economic burden of osteoporosis-related fractures in the United States, 2005–2025. J Bone Miner Res 22:465–475
3. Christiansen BA, Bouxsein ML (2010) Biomechanics of vertebral fractures and the vertebral fracture cascade. Curr Osteoporos Rep 8: 198–204
4. Schousboe JT (2016) Epidemiology of vertebral fractures. J Clin Densitom 19:8–22
5. Cooper C, Atkinson EJ, O'Fallon WM, Melton LJ (1992) Incidence of clinically diagnosed vertebral fractures: a population-based study in Rochester, Minnesota, 1985–1989. J Bone Miner Res 7:221–227

6. Freitas SS, Barrett-Connor E, Ensrud KE, Fink HA, Bauer DC, Cawthon PM, Lambert LC, Orwoll ES, Osteoporotic Fractures in Men (MrOS) Research Group (2008) Rate and circumstances of clinical vertebral fractures in older men. Osteoporos Int 19:615–623
7. Mitchell WK, Williams J, Atherton P, LarvinM LJ, Narici M (2012) Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength; a quantitative review. Front Physiol 3:1–19
8. Delmonico MJ, Harris TB, Visser M, Park SW, Conroy MB, Velasquez-Mieyer P, Boudreau R, Manini TM, Nevitt M, Newman AB, Goodpaster BH, Health, Aging, and Body (2009) Longitudinal study of muscle strength, quality, and adipose tissue infiltration. Am J Clin Nutr 90:1579–1585
9. Singh DKA, Bailey M, Lee R (2011) Ageing modifies the fibre angle and biomechanical function of the lumbar extensor muscles. Clin Biomech 26:543–547
10. Anderson DE, D'Agostino JM, Bruno AG, Demissie S, Kiel DP, Bouxsein ML (2013) Variations of CT-based trunk muscle attenuation by age, sex, and specific muscle. J Gerontol Ser A Biol Sci Med Sci 68:317–323
11. Quirk DA, Hubley-kozey CL (2014) Age-related changes in trunk neuromuscular activation patterns during a controlled functional transfer task include amplitude and temporal synergies. Hum Mov Sci Elsev BV 38:262–280
12. Dreischarf M, Aboulfazl SA, Arjmand N, Rohlmann A, Schmidt H (2016) Estimation of loads on human lumbar spine: a review of in vivo and computational model studies. J Biomech 49:833–845
13. Kato S, Murakami H, Inaki A, Mochizuki T, Demura S, Nakase J, Yoshioka K, Yokogawa N, Igarashi T, Takahashi N, Yonezawa N, Kinuya S, Tsuchiya H (2017) Innovative exercise device for the abdominal trunk muscles: an early validation study. PLoS One 12:e0172934
14. Kato S, Kurokawa Y, Tsuchiya H (2019) Development of innovative device for strengthening and strength measurement of the abdominal trunk muscles [in Japanese]. J Clinl Sports Med 36:82–87
15. Kavcic N, Grenier S, McGill SM (2004) Determining the stabilizing role of individual torso muscles during rehabilitation exercise. Spine (Phila Pa 1976) 29:1254–1265
16. Nakamura K, Ogata T (2016) Locomotive syndrome: definition and management. Clin Rev Bone Miner Metab 14:56–67
17. Genant HK, Wu CY, van Kuijk C, Nevitt MC (1993) Vertebral fracture assessment using a semiquantitative technique. J Bone Miner Res 8:1137–1148
18. Akuthota V, Ferreiro A, Moore T, Fredericson M (2008) Core stability exercise principle. Curr Sports Med Rep 7:39–44
19. Akuthota V, Nadler SF (2004) Core strengthening. Arch Phys Med Rehabil 85(3 Suppl 1):86–92
20. Hongo M, Itoi E, Sinaki M, Miyakoshi N, Shimada Y, Maekawa S, Okada K, Mizutani Y (2007) Effect of low-intensity back exercise on quality of life and back extensor strength in patients with osteoporosis: a randomized controlled trial. Osteoporos Int 18:1389–1395
21. Hongo M, Miyakoshi N, Shimada Y, Sinaki M (2012) Association of spinal curve deformity and back extensor strength in elderly women with osteoporosis in Japan and the United States. Osteoporos Int 23:1029–1034
22. Miyakoshi N, Kudo D, Hongo M, Kasukawa Y, Ishikawa Y, Shimada Y (2017) Comparison of spinal alignment, muscular strength, and quality of life between women with postmenopausal osteoporosis and healthy volunteers. Osteoporos Int 28:3153–3160
23. Sinaki M, Itoi E, Wahner HW, Wollan P, Gelzcer R, Mullan BP, Collins DA, Hodgson SF (2002) Stronger back muscles reduce the incidence of vertebral fractures: a prospective 10-year follow-up of postmenopausal women. Bone 30:836–841
24. Sinaki M, Mikkelsen BA (1984) Postmenopausal spinal osteoporosis: flexion versus extension exercises. Arch Phys Med Rehabil 65: 593–596
25. Sinaki M (2012) Exercise for patients with osteoporosis: management of vertebral compression fractures and trunk strengthening for fall prevention. PM R 4:882–888