Effects of the trunk position on muscle stiffness that reflects elongation of the lumbar erector spinae and multifidus muscles: an ultrasonic shear wave elastography study

Mitsuhiro Masaki[1,2], Xiang Ji[3], Taishi Yamauchi[4], Hiroshige Tateuchi[3], and Noriaki Ichihashi[3]

[1]Department of Physical Therapy, Niigata University of Health and Welfare, Niigata
1398 Shimami-cho, Kita-ku, Niigata 950-3198, Japan.

[2]Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata.
1398 Shimami-cho, Kita-ku, Niigata 950-3198, Japan.

[3]Department of Physical Therapy, Human Health Sciences, Graduate School of Medicine, Kyoto University, Kyoto
53 Kawahara-cho, Shogoin, Sakyo-ku, Kyoto 606-8507, Japan.

[4]Department of Rehabilitation, Anshin Clinic, Hyogo
4-1-4 Asahidori, Chuo-ku, Kobe 651-0095, Japan.

Corressp―onding author
Mitsuhiro Masaki, R.P.T., PhD.
Department of Physical Therapy, Niigata University of Health and Welfare
Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare
1398 Shimami-cho, Kita-ku, Niigata 950-3198, Japan.
E-mail: masaki@nuhw.ac.jp

Abstract

Purpose The present study aimed to clarify the effects of the trunk position on muscle stiffness that reflects elongation of the lumbar erector spinae and lumbar multifidus muscles using ultrasonic shear wave elastography (SWE).

Methods The study included ten healthy men. The shear elastic modulus of the left lumbar erector spinae and lumbar multifidus muscles were evaluated using ultrasonic SWE. Measurement postures for the left lumbar erector spinae muscle were (1) prone position (Rest), (2) sitting position with the trunk flexed (Flexion), (3) the Flexion position adding right trunk lateral flexion (Flexion-Lateral Flexion), and (4) the Flexion position adding right trunk rotation (Flexion-Rotation 1). The left lumbar multifidus muscle were measured in positions (1)-(3), and (5) the Flexion position adding left trunk rotation (Flexion-Rotation 2).

Results The shear elastic modulus of the lumbar erector spinae muscle in the Flexion-Lateral Flexion position was significantly higher than that in the Rest, Flexion, or Flexion-Rotation 1 positions. Shear elastic modulus of the lumbar multifidus muscle was similar in the Flexion, Flexion-Lateral Flexion, and Flexion-Rotation 2 positions, but significantly lower in the Rest position.

Conclusions The results of the present study suggest that the lumbar erector spinae muscle is stretched effectively in the position adding trunk contralateral lateral flexion to flexion. The results also indicate that the lumbar multifidus muscle, which does not appear to be affected by adding trunk

contralateral lateral flexion or ipsilateral rotation to flexion, is stretched effectively in the trunk flexion position.

Keywords Paraspinal muscles・Muscle elongation・Muscle stiffness・Ultrasonography

Introduction

Low back pain (LBP) can be attributed to several factors, such as intervertebral disks, intervertebral joints, ligaments, nerves, vertebral body, and lumbar back muscles, while there is a substantial incidence of non-specific LBP with unknown pathologies (Oliveira et al. 2018). Our previous study (Masaki et al. 2017) using ultrasonic shear wave elastography (SWE) demonstrated that muscle stiffness of the lumbar multifidus muscle in the prone position is high while that of the lumbar erector spinae muscle is unchanged in LBP patients compared to healthy subjects. The results of that study suggested that LBP is associated with increased muscle stiffness of the lumbar multifidus muscle rather than muscle stiffness of the lumbar erector spinae muscle. Furthermore, because muscle shortening of the lumbar erector spinae muscle, caused by inactivity, leads to a decreased range of trunk motion, stretching of that muscle is performed to promote muscle lengthening (Moore et al. 2015; Sherman et al. 2010). Thus, clarification of the effective stretching position of the lumbar erector spinae and multifidus muscles is significant in rehabilitation.

The lumbar erector spinae muscle, a member of the superficial muscles of the trunk, has a long moment arm (MA), which is the distance between the joint center and the muscle, for the trunk (Chaffin et al. 1990; Dumas et al. 1991; Jorgensen et al. 2001; Lin et al. 2001; Moga et al. 1993). The lumbar erector spinae muscle has the action of trunk extension, ipsilateral lateral flexion, and ipsilateral rotation. In general, the muscle is effectively stretched in positions opposite to the direction of the muscle action. In rehabilitation, the lumbar erector spinae muscle is frequently stretched in the trunk flexion position (Moore et al. 2015; Sherman et al. 2010). However, considering its muscle action, the lumbar erector spinae muscle may be stretched effectively in the position adding contralateral lateral flexion or contralateral rotation to flexion. On the other hand, the lumbar multifidus muscle, a member of the deep muscles of the trunk, has a short MA for the trunk (McGill et al. 1993). The lumbar multifidus muscle has the action of trunk extension, ipsilateral lateral flexion, and contralateral rotation. Thus, the lumbar multifidus muscle may be stretched effectively in the position adding contralateral lateral flexion or ipsilateral rotation to flexion. However, it has been difficult to assess muscle elongation of the individual lumbar back muscle isolating subcutaneous fat and fibrous tissue quantitatively. Thus, the effective stretching position of the lumbar erector spinae and multifidus muscles remains unclear.

The quantitative assessment of muscle stiffness that reflects elongation of the individual muscle has become possible by the shear elastic modulus measured using SWE. The shear elastic modulus measured by SWE reflects muscle elongation such as the length of muscle-tendon units or passive muscle force in lower extremity muscles (Koo et al. 2013; Maïsetti et al. 2012), and is associated with upper extremity muscle strength (Ateş et al. 2015). The shear elastic modulus is a measure of muscle stiffness, which can be used as an indirect measure of muscle length or force generation in upper and lower extremity muscles. Previous studies (Moreau et al. 2016; Creze et al. 2017; Kelly et al. 2018), which targeted the lumbar back muscles, also demonstrated that the shear elastic modulus measured using SWE is a feasible method for quantifying muscle stiffness of the lumbar erector spinae and multifidus muscles.

Furthermore, a previous study using SWE examined the effective stretching position by assessing muscle stiffness that reflects elongation of the upper extremity muscles such as the infraspinatus, teres minor, and deltoid muscles (Umehara et al. 2017a). Previous studies also demonstrated the effects of the upper or lower extremity position on muscle stiffness that reflects elongation of the upper extremity muscles such as pectoralis minor muscle (Umehara et al. 2017b), and the lower extremity muscles, such as the semitendinosus, biceps femoris (Umegaki et al. 2015) and tensor fasciae latae (Umehara et al. 2015) muscles. However, no previous study examined the effects of the trunk position on muscle elongation of the lumbar erector spinae or the multifidus muscles using SWE.

Therefore, the present study aimed to assess muscle stiffness that reflects elongation of the stretched lumbar erector spinae and multifidus muscles using SWE in healthy young men, and to identify the effects of the trunk position on muscle elongation of the lumbar back muscles. We hypothesized that the lumbar erector spinae muscle is effectively stretched in the position adding trunk contralateral lateral flexion or contralateral rotation to flexion, and the lumbar multifidus muscle is effectively stretched in the position adding contralateral lateral flexion or ipsilateral rotation to flexion.

Methods

Participants

Ten healthy young men (age, 22.9 ± 2.3 years; body height, 171.0 ± 4.9 cm; body weight, 65.3 ± 6.2 kg [mean ± standard deviation]) in Kyoto University, Japan, were included in the present study. The subjects with LBP at the time of evaluation, severe orthopedic disorder other than LBP, neurological, respiratory or circulatory disorders in the present, or previous spinal surgery were excluded.

The protocol was approved by the Ethics Committee of the Kyoto University Graduate School and the Faculty of Medicine. Written informed consent was provided by all participants.

Priori sample size estimation

The sample size was calculated using G*Power software, version 3.1.9.2 (Franz Faul, University of Kiel, Kiel, Germany). Power analysis demonstrated that the sample size needed for the present study was 10 subjects, with an effect size of 0.40, an α error probability of 0.05, and a statistical power of 0.80.

Ultrasound measurement

An ultrasound imaging device with SWE (Aixplorer, Supersonic Imagine, Aix-en-Provence, France) was utilized for muscle stiffness measurement that reflects elongation of the lumbar back muscles. Longitudinal ultrasound images of the left lumbar erector spinae (iliocostalis lumborum) and multifidus muscles were taken once using the B-mode of the ultrasound imaging device with a linear array probe (SuperLinear 10-2), which was laid parallel to the muscle fibers to assess muscle elongation accurately, as previously described (Masaki et al. 2017). The measurement site of the lumbar back muscles was 7 cm lateral from the L3 spinous process for the lumbar erector spinae muscle, and 2 cm lateral to the L4 spinous process for the lumbar multifidus muscle (Masaki et al. 2017).

Measurement postures for muscle elongation of the left lumbar erector spinae muscle were as follows: (1) the prone position (Rest), (2) the sitting position with the hip and knee joints in full flexion beneath them and with the trunk position of 40-45° flexion to stretch for the lumbar back muscles (Flexion), (3) the Flexion position adding 30° right trunk lateral flexion (Flexion-Lateral Flexion), and (4) the Flexion position adding 30° right trunk rotation (Flexion-Rotation 1). Measurement postures for muscle elongation of the left lumbar multifidus muscle were as follows: (1) the Rest position, (2) the Flexion position, (3) the Flexion-Lateral Flexion position, and (5) the Flexion position adding 30° left trunk rotation (Flexion-Rotation 2). These positions were chosen on the assumption that the lumbar erector spinae and multifidus muscles would be stretched sufficiently in the positions opposite to the direction of muscle action.

The subjects maintained a relaxed state as much as possible while leaning against a stretch pole with towels placed under their stomach and against the assistance of a tester to maintain measurement postures in the Flexion, Flexion-Lateral Flexion, and Flexion-Rotation positions. Another tester operated a linear array probe of an ultrasound imaging device (Fig.1). Trunk angle in measurement postures was set using a goniometer. Measurement postures were assigned in a random order to each subject.

The shear elastic modulus of the lumbar erector spinae and multifidus muscles was evaluated by measuring the shear wave propagation speed in the tissues generated using SWE in each measurement posture (Fig. 2). In analyses for muscle elongation, the circular regions of interest (ROIs) were set manually in the color-coded box presentation (approximately 3 cm × 3 cm) on a B-mode ultrasound imaging. Three ROIs with a diameter of 10 mm were set in the color-coded box, with one located at the center of the box and the other two inferior to the initial ROI. The mean shear elastic modulus values in each ROI and the mean values of the three ROIs were calculated. Furthermore, the shear elastic modulus from the muscle mass density and the shear wave propagation speed is computed (Aubry et al. 2013). The enhanced shear elastic modulus indicates high muscle elongation. Intraclass correlation coefficients (ICC 1.1) for the lumbar erector spinae muscle and lumbar multifidus muscle in one measurement of the shear elastic modulus using SWE were 0.784 and 0.913, respectively, which are high values (Masaki et al. 2017). The ROIs were determined by the same examiner. The shear elastic modulus was automatically calculated from an ultrasound imaging device.

Statistical analyses

Statistical analysis was performed using SPSS version 20.0 (IBM Japan; Tokyo, Japan). The differences in the shear elastic modulus of the lumbar erector spinae and lumbar multifidus muscles in each measurement posture were analyzed by repeated-measures analysis of variance or Friedman tests after normality of the variable was examined by Shapiro-Wilk tests. If a significant primary effect was found, pairwise comparisons were performed by post hoc Bonferroni or Bonferroni correction using Wilcoxon signed-rank test. *P* values of <0.05 were considered statistically significant. *P* values from Wilcoxon signed-rank test were multiplied by 6 in Bonferroni correction.

Results

Repeated-measures analysis of variance and Friedman test showed that there was a significant primary effect on measurement posture in the lumbar erector spinae and lumbar multifidus muscles. Following post hoc multiple comparisons, the shear elastic modulus of the lumbar erector spinae muscle (Fig. 3) in the Flexion (mean ± standard deviation, 13.7 ± 4.2 kPa; standard error, 1.3) and Flexion-Lateral Flexion (mean ± standard deviation, 20.3 ± 8.4 kPa; standard error, 2.6) positions was shown to be significantly higher than that in the Rest position (mean ± standard deviation, 5.0 ± 1.1 kPa; standard error, 0.3) (Rest × Flexion; $p < 0.01$, Rest × Flexion-Lateral Flexion; $p < 0.01$). Furthermore, the shear elastic modulus of the lumbar erector spinae muscle in the Flexion-Lateral Flexion position was significantly higher than that in the Flexion and Flexion-Rotation 1 positions (mean ± standard deviation, 9.2 ± 2.7 kPa; standard error, 0.8) (Flexion × Flexion-Lateral Flexion; $p = 0.03$, Flexion-Lateral Flexion × Flexion-Rotation 1; $p < 0.01$). No significant difference was seen in the other comparisons (Rest × Flexion-Rotation 1; $p = 0.36$, Flexion × Flexion-Rotation 1; $p = 0.30$).

The shear elastic modulus of the lumbar multifidus muscle (Fig. 4) in the Flexion (mean ± standard deviation, 30.5 ± 9.5 kPa; standard error, 3.0), Flexion-Lateral Flexion (mean ± standard deviation, 26.0 ± 6.4 kPa; standard error, 2.0), and Flexion-Rotation 2 (mean ± standard deviation, 27.5 ± 12.8 kPa; standard error, 4.0) positions was significantly higher than that in the Rest position (mean ± standard deviation, 5.8 ± 1.6 kPa; standard error, 0.5) (Rest × Flexion; $p = 0.03$, Rest × Flexion-Lateral Flexion; $p = 0.03$, Rest × Flexion-Rotation 2; $p = 0.03$). No significant difference was seen in the other comparisons, and there was no significant difference in the shear elastic modulus of the lumbar multifidus muscle between the Flexion, Flexion-Lateral Flexion, and Flexion-Rotation 2 positions (Flexion × Flexion-Lateral Flexion; $p = 0.99$, Flexion × Flexion-Rotation 2; $p = 0.99$, Flexion-Lateral Flexion ×Flexion-Rotation 2; $p = 0.99$).

Discussion

We assessed muscle stiffness that reflects elongation of the lumbar erector spinae and multifidus muscles in a variety of the trunk position in healthy young men. In the present study, the lumbar erector spinae muscle was stretched effectively in the position adding contralateral lateral flexion to flexion, which was consistent with our hypothesis. On the other hand, the shear elastic modulus of the lumbar multifidus muscle was not affected by adding trunk contralateral lateral flexion or ipsilateral rotation to flexion, but was stretched effectively in the trunk flexion position. These results are not consistent with our hypothesis. To the best of our knowledge, the present study is the first to assess muscle stiffness that reflects elongation of the stretched lumbar erector spinae and multifidus muscles individually and quantitatively, by using SWE in healthy young men, and to clarify the effects of the trunk position on muscle elongation of the lumbar back muscles.

The lumbar erector spinae muscle, a member of the superficial muscles of the trunk, is capable of generating the extension moment due to the long distance between the joint center and the muscle, and has a long extension moment arm (MA) for the trunk (Chaffin et al. 1990; Dumas et al. 1991; Jorgensen et al. 2001; Lin et al. 2001; Moga et al. 1993). A previous study (McGill et al. 1993) demonstrated that extension MA and ipsilateral lateral flexion MA for the trunk of the lumbar erector spinae muscle measured in the lumbar spine were 6.1 ± 0.6 cm and 2.2 ± 0.4 cm, respectively. These findings suggest that although ipsilateral lateral flexion MA of the lumbar erector spinae muscle is shorter than extension MA, the muscle acts as trunk ipsilateral lateral flexor. This observation is consistent with our results that the lumbar erector spinae muscle is more stretched in the position adding trunk contralateral lateral flexion to flexion, which is opposite to the muscle action.

On the other hand, we initially hypothesized that muscle elongation of lumbar erector spinae muscle might also be higher in the Flexion-Rotation 1 position, which is the position of trunk contralateral rotation, because this muscle has ipsilateral rotation MA (i.e. acts as ipsilateral rotator) of the trunk. However, muscle elongation of the lumbar erector muscle in the Flexion-Lateral Flexion position was significantly higher than that in the Flexion-Rotation 1 position. This observation suggests that the lumbar erector spinae muscle was stretched effectively in the position adding trunk contralateral lateral flexion rather than contralateral rotation to flexion. A previous study (Maganaris et al. 2000) demonstrated that the MA of the muscle is calculated by dividing the stretched amount of muscle-tendon unit by the change of joint angle using the tendon-excursion methods. Based on that study, it is assumed that the muscle-tendon unit is more stretched when the MA of the muscle is longer or the change in joint angle is higher. Although no study has examined the ipsilateral rotation MA for the trunk of the lumbar erector spinae muscle, we postulate that it may be shorter than the ipsilateral lateral flexion MA. Thus, it is assumed that the lumbar erector spinae muscle was stretched effectively in the position adding trunk contralateral lateral flexion rather than the contralateral rotation to flexion. In rehabilitation, the stretching method for the lumbar erector spinae muscle is generally performed using the trunk flexion position (Moore et al. 2015; Sherman et al. 2010). However, the results of the present study show that the lumbar erector spinae muscle is stretched effectively in the position adding trunk contralateral lateral flexion to flexion rather than the trunk flexion position or the position adding trunk contralateral rotation to flexion. The results of the present study also show that this is only a unilateral effect, and the lumbar erector spinae muscle during trunk contralateral rotation likely do not experience any added benefits.

Trunk extension and ipsilateral lateral flexion MA for the trunk of the lumbar multifidus muscle, a member of the deep muscle of the trunk, are shorter than those of the superficial muscles of the trunk, such as the lumbar erector spinae muscle (McGill et al. 1993). Although the lumbar multifidus muscle is advantageous in stabilizing the lumbar spine by increasing the compressive force (Bergmark. 1989; MacDonald et al. 2006), it is disadvantageous for generating the joint movement. A previous study (McGill et al. 1993) demonstrated that the extension MA (5.5 ± 0.7 cm) for the trunk of the lumbar multifidus muscle measured in the lumbar spine is shorter than the extension MA (6.1 ± 0.6 cm) for the trunk of the lumbar erector spinae muscle, although the extension MA for the former muscle is comparatively long. The lumbar multifidus muscle has the action of ipsilateral lateral flexion and contralateral rotation of the trunk. However, the ipsilateral lateral flexion MA (1.1 ± 0.1 cm) for the trunk of the lumbar multifidus muscle measured in the lumbar spine is shorter than the extension MA (5.5 ± 0.7 cm) for the trunk, and the ipsilateral lateral flexion MA for the trunk is short (McGill et al. 1993). Furthermore, although no previous study has described the trunk rotation MA of the lumbar multifidus muscle, the contralateral rotation MA may be shorter than the extension MA. Thus, it is assumed that the lumbar multifidus muscle was not stretched effectively in the position adding contralateral lateral flexion or ipsilateral rotation to flexion. The results of the present study clarified that the lumbar multifidus muscle is stretched effectively in the trunk flexion position without adding trunk contralateral lateral flexion or ipsilateral rotation.

There are several limitations in the present study. First, the shear elastic modulus measured by SWE assessed muscle stiffness that reflects elongation but not directly muscle elongation. Second, as the present study included only young men, it is unclear if the results can be applied to other age and sex groups. Third, we did not assess muscle elongation of the lumbar back muscles in the trunk flexion position adding trunk lateral flexion and rotation to flexion simultaneously. Fourth, although we examined the effects of the trunk position on muscle elongation of the lower back muscle in healthy subjects, performing stretching of the lumbar back muscle, proposed in the present study, requires attention in athletes (Hangai et al. 2009; Kaneoka et al. 2007) and elderly individuals (Hangai et al. 2008) with degenerative intervertebral discs.

Conclusions

The results of the present study suggest that the lumbar erector spinae muscle is stretched effectively in the position adding trunk contralateral lateral flexion to flexion. The results also indicate that the lumbar multifidus muscle is stretched effectively in the trunk flexion position and is not affected by adding trunk contralateral lateral flexion or ipsilateral rotation to flexion.

Acknowledgments This study was supported by the Grant - in - Aid for Scientific Research (B) 15H03043. The authors wish to thank all of the individuals who participated in the present study.

Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest. No funding sources were used for the present study.

References

Ateş, F., Hug, F., Bouillard, K., Jubeau, M., Frappart, T., Couade, M., Bercoff, J., Nordez, A., 2015. Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity. J. Electromyogr. Kinesiol. 25, 703-708.

Aubry, S., Risson, J.R., Kastler, A., Barbier-Brion, B., Siliman, G., Runge, M., Kastler, B., 2013. Biomechanical properties of the calcaneal tendon in vivo assessed by transient shear wave elastography. Skeletal. Radiol. 42, 1143-1150.

Bergmark, A., 1989. Stability of the lumbar spine. A study in mechanical engineering. Acta. Orthop. Scand. Suppl. 230, 1-54.

Chaffin, D.B., Redfern, M.S., Erig, M., Goldstein, S.A., 1990. Lumbar muscle size and locations from CT scans of 96 women of age 40 to 63 years. Clin. Biomech. (Bristol, Avon) 5, 9-16.

Creze, M., Nyangoh Timoh, K., Gagey, O., Rocher, L., Bellin, M.F., Soubeyrand, M., 2017. Feasibility assessment of shear wave elastography to lumbar back muscles: A Radioanatomic Study. Clin. Anat. 30, 774-780.

Dumas, G.A., Poulin, M.J., Roy, B., Gagnon, M., Jovanovic, M., 1991. Orientation and moment arms of some trunk muscles. Spine (Phila Pa 1976) 16, 293-303.

Hangai, M., Kaneoka, K., Kuno, S., Hinotsu, S., Sakane, M., Mamizuka, N., Sakai, S., Ochiai, N., 2008. Factors associated with lumbar intervertebral disc degeneration in the elderly. Spine. J. 8, 732-740.

Hangai, M., Kaneoka, K., Hinotsu, S., Shimizu, K., Okubo, Y., Miyakawa, S., Mukai, N., Sakane, M., Ochiai, N., 2009. Lumbar intervertebral disk degeneration in athletes. Am. J. Sports. Med. 37, 149-155.

Jorgensen, M.J., Marras, W.S., Granata, K.P., Wiand, J.W., 2001. MRI-derived moment-arms of the female and male spine loading muscles. Clin. Biomech. (Bristol, Avon) 16, 182-193.

Kaneoka, K., Shimizu, K., Hangai, M., Okuwaki, T., Mamizuka, N., Sakane, M., Ochiai, N., 2007. Lumbar intervertebral disk degeneration in elite competitive swimmers: a case control study. Am. J. Sports. Med. 35, 1341-1345.

Kelly, J.P., Koppenhaver, S.L., Michener, L.A., Proulx, L., Bisagni, F., Cleland, J.A., 2018. Characterization of tissue stiffness of the infraspinatus, erector spinae, and gastrocnemius muscle using ultrasound shear wave elastography and superficial mechanical deformation. J. Electromyogr. Kinesiol. 38, 73-80.

Koo, T.K., Guo, J.Y., Cohen, J.H., Parker, K.J., 2013. Relationship between shear elastic modulus and passive muscle force: an ex-vivo study. J. Biomech. 46, 2053-2059.

Lin, Y.H., Chen, C.S., Cheng, C.K., Chen, Y.H., Lee, C.L., Chen, W.J., 2001. Geometric parameters of the in vivo tissues at the lumbosacral joint of young Asian adults. Spine (Phila Pa 1976) 26, 2362-2367.

MacDonald, D.A., Moseley, G.L., Hodges, P.W., 2006. The lumbar multifidus: does the evidence support clinical beliefs? Man. Ther. 11, 254-263.

Maganaris, C.N., Baltzopoulos, V., Sargeant, A.J., 2000. In vivo measurement-based estimations of the human Achilles tendon moment arm. Eur. J. Appl. Physiol. 83, 363-369.

Maïsetti, O., Hug, F., Bouillard, K., Nordez, A., 2012. Characterization of passive elastic properties of the human medial gastrocnemius muscle belly using supersonic shear imaging. J. Biomech. 45, 978-984.

Masaki, M., Aoyama, T., Murakami, T., Yanase, K., Ji, X., Tateuchi, H., Ichihashi, N., 2017. Association of low back pain with muscle stiffness and muscle mass of the lumbar back muscles, and sagittal spinal alignment in young and middle-aged medical workers. Clin. Biomech. (Bristol, Avon) 49, 128-133.

McGill, S.M., Santaguida, L., Stevens, J., 1993. Measurement of the trunk musculature from T5 to L5 using MRI scans of 15 young males corrected for muscle fibre orientation. Clin. Biomech. (Bristol, Avon) 8, 171-178.

Moga, P.J., Erig, M., Chaffin, D.B., Nussbaum, M.A., 1993. Torso muscle moment arms at intervertebral levels T10 through L5 from CT scans on eleven male and eight female subjects. Spine (Phila Pa 1976) 18, 2305-2309.

Moore, A., Mannion, J., Moran, R.W., 2015. The efficacy of surface electromyographic biofeedback assisted stretching for the treatment of chronic low back pain: a case-series. J. Bodyw. Mov. Ther. 19, 8-16.

Moreau, B., Vergari, C., Gad, H., Sandoz, B., Skalli, W., Laporte, S., 2016. Non-invasive assessment of human multifidus muscle stiffness using ultrasound shear wave elastography: A feasibility study.

Proc. Inst. Mech. Eng. H. 230, 809-814.

Oliveira, C.B., Maher, C.G., Pinto, R.Z., Traeger, A.C., Lin, C.C., Chenot, J.F., van, Tulder, M., Koes, B.W., 2018. Clinical practice guidelines for the management of non-specific low back pain in primary care: an updated overview. Eur. Spine. J. 27, 2791-2803.

Sherman, K.J., Cherkin, D.C., Cook, A.J., Hawkes, R.J., Deyo, R.A., Wellman, R., Khalsa, P.S., 2010. Comparison of yoga versus stretching for chronic low back pain: protocol for the Yoga Exercise Self-care (YES) trial. Trials 11, 36.

Umegaki, H., Ikezoe, T., Nakamura, M., Nishishita, S., Kobayashi, T., Fujita, K., Tanaka, H., Ichihashi, N., 2015. The effect of hip rotation on shear elastic modulus of the medial and lateral hamstrings during stretching. Man. Ther. 20, 134-137.

Umehara, J., Ikezoe, T., Nishishita, S., Nakamura, M., Umegaki, H., Kobayashi, T., Fujita, K., Ichihashi, N., 2015. Effect of hip and knee position on tensor fasciae latae elongation during stretching: An ultrasonic shear wave elastography study. Clin. Biomech. (Bristol, Avon) 30, 1056-1059.

Umehara, J., Hasegawa, S., Nakamura, M., Nishishita, S., Umegaki, H., Tanaka, H., Fujita, K., Kusano, K., Ichihashi, N., 2017a. Effect of scapular stabilization during cross-body stretch on the hardness of infraspinatus, teres minor, and deltoid muscles: An ultrasonic shear wave elastography study. Musculoskelet. Sci. Pract. 27, 91-96.

Umehara, J., Nakamura, M., Fujita, K., Kusano, K., Nishishita, S., Araki, K., Tanaka, H., Yanase, K., Ichihashi, N., 2017b. Shoulder horizontal abduction stretching effectively increases shear elastic modulus of pectoralis minor muscle. J. Shoulder. Elbow. Surg. 26, 159-1165.

Abbreviations

ICC Intraclass correlation coefficient

LBP Low back pain

MA Moment arm

ROI Region of interest

SWE Shear wave elastography

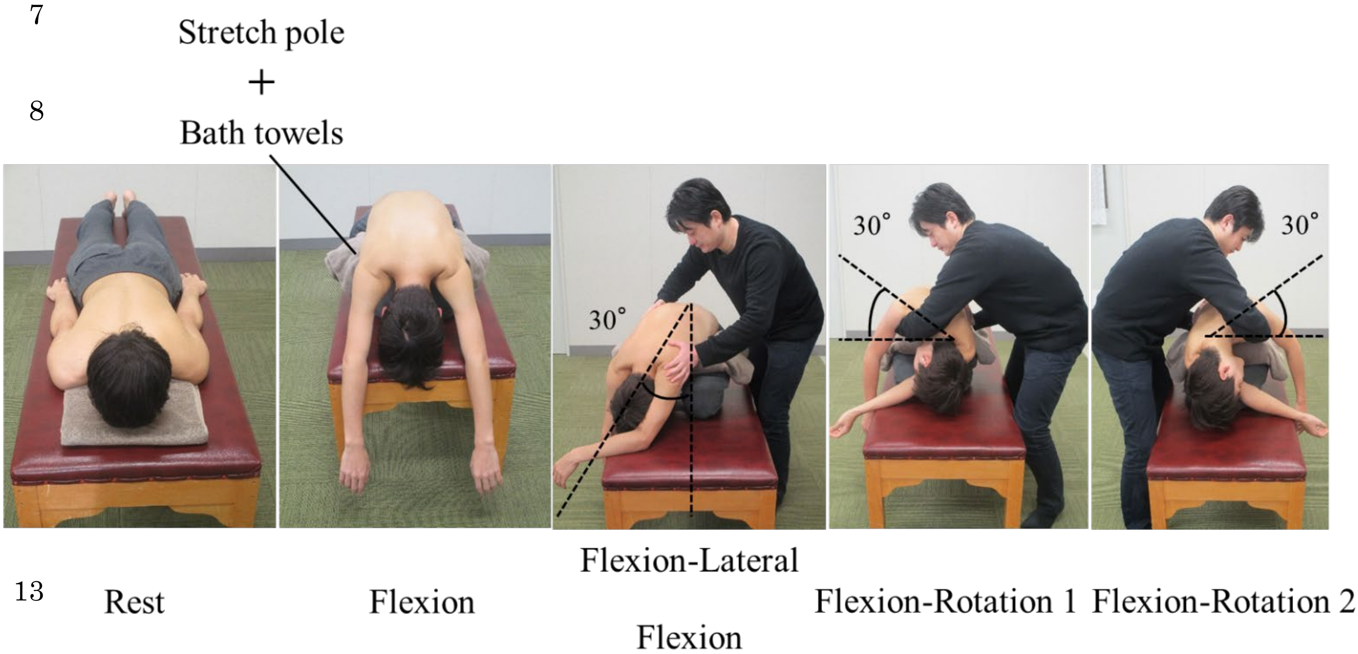

Fig. 1 Muscle stiffness measurement that reflects elongation of the lumbar back muscles in the Flexion, Flexion-Lateral Flexion, and Flexion-Rotation positions.

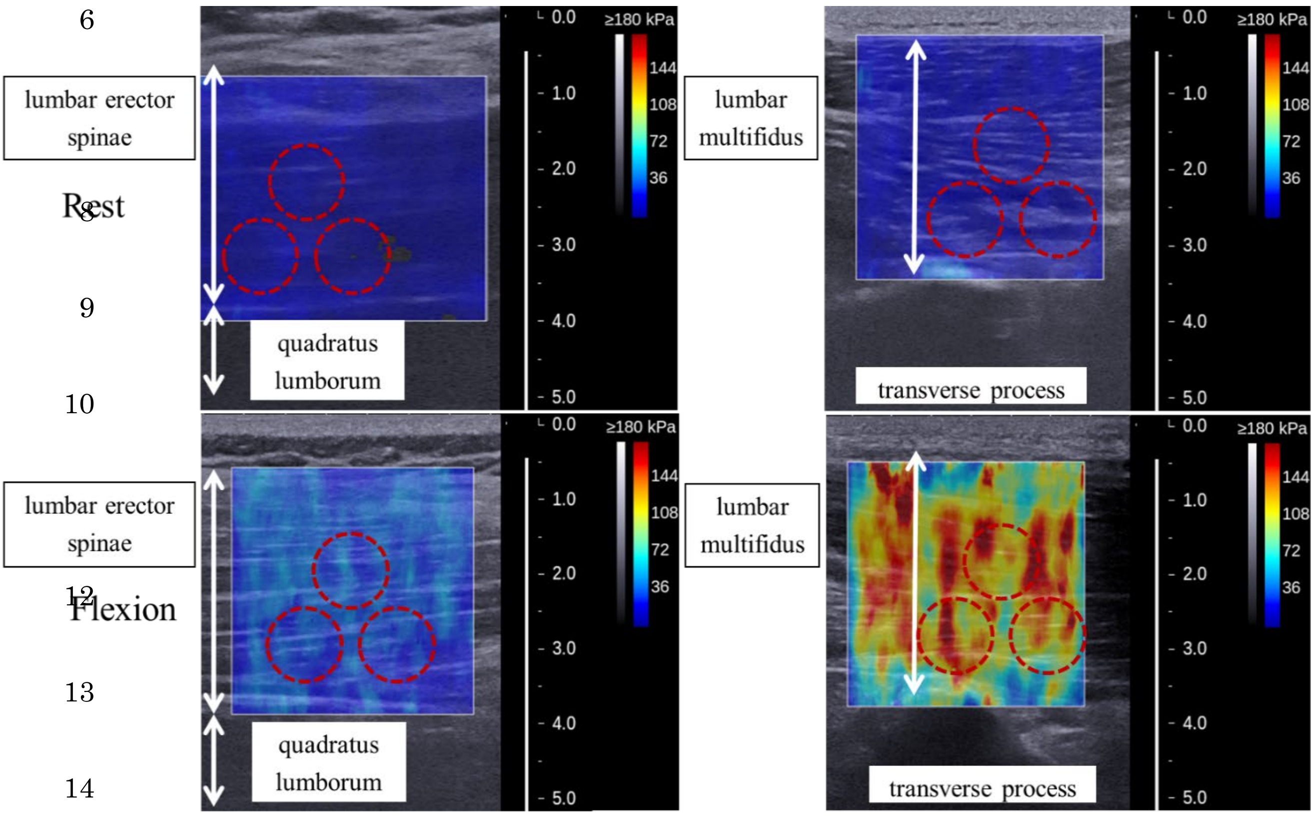

Fig. 2 Muscle stiffness measurement that reflects elongation of the lumbar back muscles in the Rest and Flexion positions.

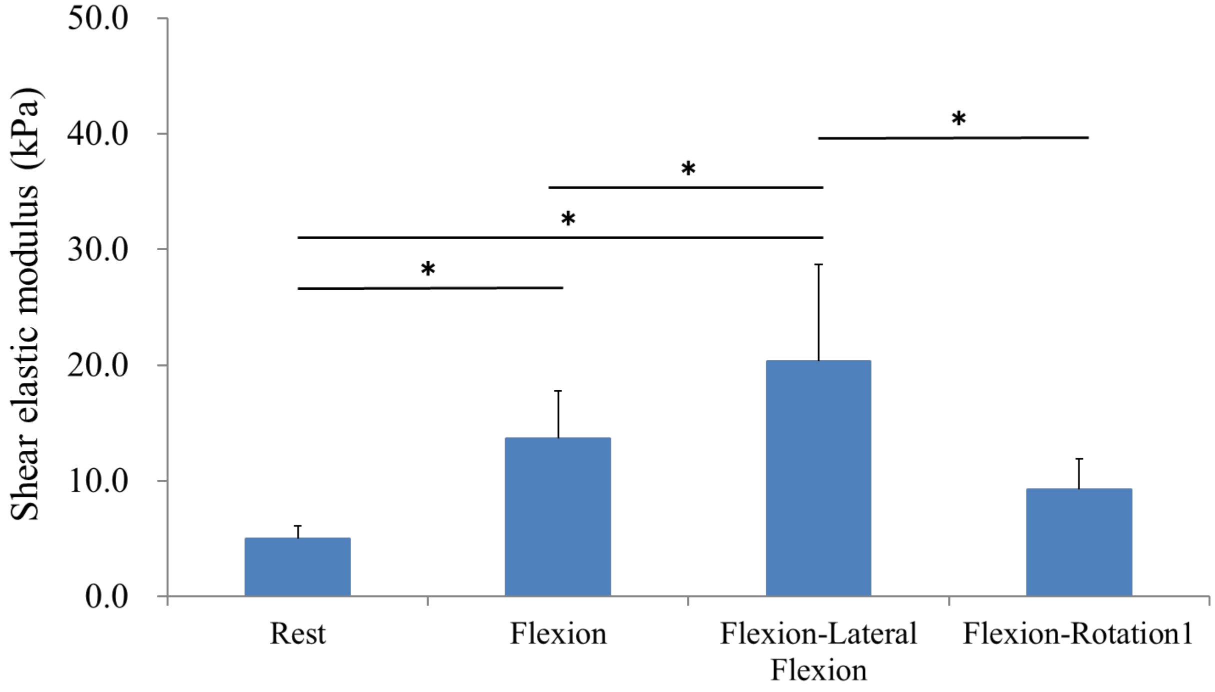

Fig. 3 The shear elastic modulus of the lumbar erector spinae muscle in each measurement posture.

Error bar: standard deviation.

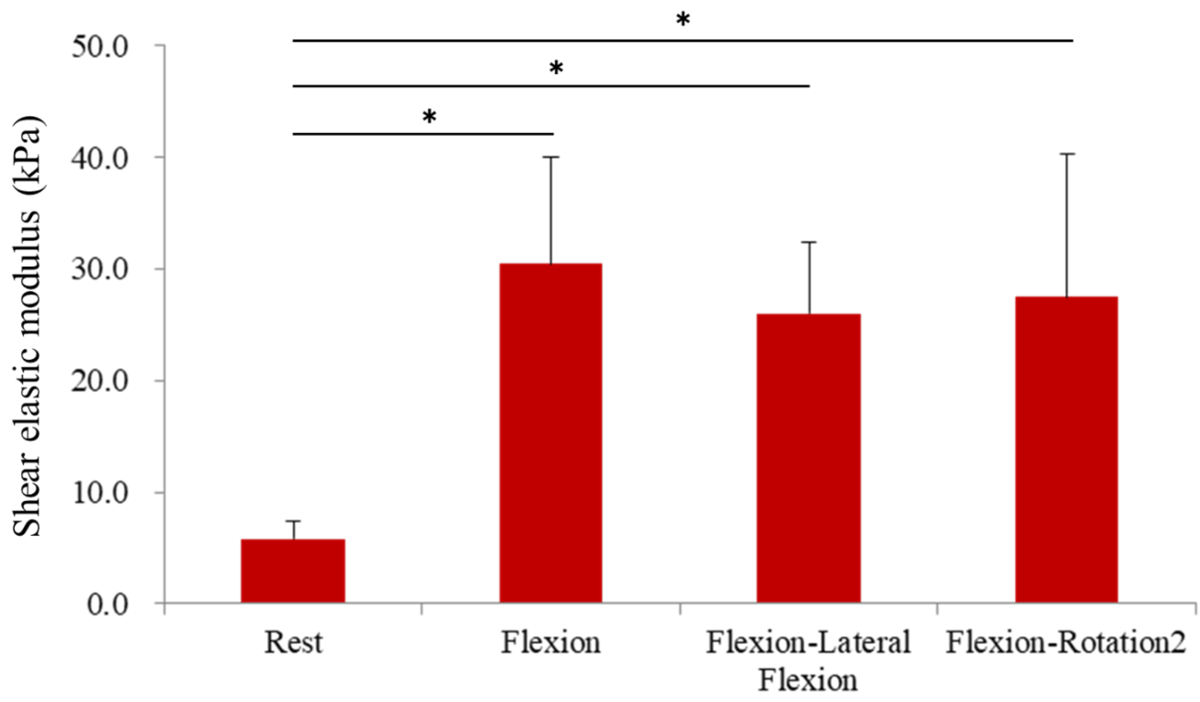

Fig. 4 The shear elastic modulus of the lumbar multifidus muscle in each measurement posture.

Error bar: standard deviation.