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Original Article

The Components of Lumbar Motor Control Are Not Inter-related

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Abstract

Objectives: To verify the relationship between the indicators of components of lumbar motor control and determine the factors related to the indicators to each of these components. **Methods**: Twenty-five healthy university students were included in the study. The lumbar spine and hip kinematic parameters of posterior/anterior pelvic tilt (mobility and smoothness), ball catching (reactivity), and forward/backward rocking (adaptive stability) were measured as indicators of lumbar motor control. Lumbar proprioception, trunk muscle strength, and lower trunk muscle thickness were also measured. Kinematic parameters of the lumbar spine and hip were measured using a small accelerometer. The data verified the relevance of indicators of lumbar motor control and the relationship with relevant factors. **Results**: No significant correlations were found for most lumbar motor control indicators. Lumbar proprioception and rectus abdominis muscle thickness were identified as relevant indicators of lumbar motor control. **Conclusions**: Each component of lumbar motor control is independent and must be evaluated for the component whose function is required. Additionally, some components of lumbar motor control are associated with lumbar proprioception and rectus abdominis muscle thickness; thus, evaluation of these components is necessary when evaluating lumbar motor control.

Keywords: Evaluation, Kinematics, Lumbar Spine, Motor Control, Proprioception

Introduction

Although the relationship between lumbar motor control and various pathological conditions and disorders is well-established, the importance of lumbar motor control remains unclear. Lumbar motor control is closely related to lower back pain because reduced lumbar spine motion, delayed motion velocity, and excessive lumbar motion induce lower back pain[1,2]. Lumbar motor control is important not only for lumbar disorders, but also for balance ability, gait function, and the ability to perform activities of daily living in patients with stroke and older individuals[3-5], as well as in high performance activities such as by athletes[6]. Therefore, evaluation of lumbar motor control and training based on it is widely conducted.

The term "motor control" has a broad meaning, and there are a variety of indicators used to assess motor control. Motor control is in the methods by which the nervous system controls posture and movements to perform specific motor tasks[7]. Motor control includes components such as the magnitude of motion, smoothness of motion, balance of muscle groups, and reactivity. A wide variety of motor control indicators have been established. Lumbar motor control has been investigated from various perspectives including the magnitude (too large or too small) of lumbar motion[7], and the amount and timing of muscle activity during task execution[8-10]. Furthermore, lumbar motor control often involves not only the lumbar region but also its relative relationship with other surrounding regions such as the hip and thoracic spine[11,12]. Thus, lumbar motor control has a broad meaning, and when used, it is necessary to clarify which component is used as an indicator.

Although several factors are involved in lumbar motor

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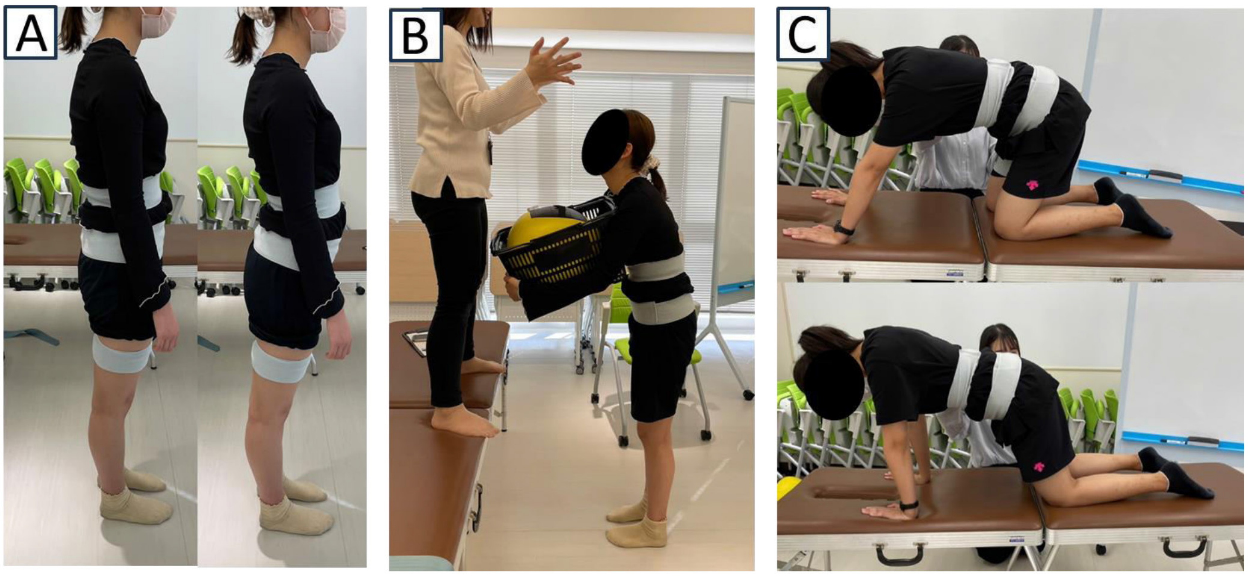

Figure 1. Measurement of each motor-control component. A: Pelvic tilt (posterior tilt in the left figure, anterior tilt in the right figure), B: Ball catching, C: Rocking (backward in the upper figure, forward in the lower figure).

control, assessment of lumbar motor control often involves combining these factors. Problems with one factor often mean that other factors are equally problematic. A comprehensive evaluation battery including several components of lumbar motor control has been developed[13,14], however, whether each component is actually related has not been investigated. It is important to clarify the relevance of each component of lumbar motor control, as this will help identify whether each component of lumbar motor control needs to be evaluated accordingly.

In addition, motor control results from the interaction between motor output (primarily the muscle) and sensory input[15]. Therefore, motor control may involve structures such as the muscle cross-sectional area, which is related to motor output[16] and proprioceptive functions. Although reports investigating the factors associated with specific components of motor control have been published, none of them have investigated the factors associated with each component of motor control. Identification of the factors associated with each component of lumbar motor control might enable developing interventions to improve this phenomenon.

This study aimed to evaluate the relationship between the indicators of each component of lumbar motor control and to determine the factors associated with each of these components. As each component of lumbar motor control differs, we hypothesized that the indicators of each component would be independent of the other components.

Methods

Study design, participants and setting

This was a cross-sectional study. The participants were university students aged 20–25 years who were willing to cooperate after being invited to participate in the study in September 2023. The exclusion criteria were as follows: 1) pain that interfered with daily life; 2) physical dysfunction, such as paralysis due to cerebrovascular disease; 3) history of surgery that significantly affected the spinal column or hip motion, for example, spinal fusion or total hip arthroplasty; 4) significant spinal column deformation; 5) cognitive decline that prevented them from understanding the study; and 6) pregnancy. Twenty-five participants (12 men and 13 women, age 21.9±0.8 years, height 165.4±8.6 cm, weight 57.7±8.0 kg) were included in the study, and measurements were taken between October and November 2023. All measurements were performed at the authors' institutions.

Measurements

The lumbar motor control, lumbar proprioception, trunk muscle strength, and trunk muscle thickness were measured. The indicators of lumbar motor control were the lumbar spine and hip motion angles and lumbar angular jerk cost during pelvic tilt (posterior/anterior) in the standing position, ball catching with closed eyes, and rocking four-point kneeling (backward/forward), in accordance with previous studies[13,14] (Figure 1).

All the tasks were practiced in advance. A small accelerometer (AMWS020, ATR-Promotions, Sagara, Japan)

Table 1. Calculation formula for each measurement.

$Angular\ Jerk\ Cost=\int_{t0}^{t}\left(\frac{d^3\theta}{dt^3}\right)^2 dt$	
$Constant\ error=\frac{\sum_{i=1}^{n}(xi-T)}{n}$	where, "xi" is the final position of a single trial, "T" is the target position and "n" is the number of trials.
$Absolute\ error=\frac{\sum_{i=1}^{n}\lvert xi-T\rvert}{n}$	where, "xi" is the final position of a single trial, "T" is the target position and "n" is the number of trials.
$Variable\ error=\sqrt{\frac{\sum_{i=1}^{n}(xi-\bar{X})^2}{n}}$	where, "xi" is the final position of a single trial, "n" is the number of trials and "$\bar{X}$" is the mean of the trials.

and receiver software (sensor controller, ATR-Promotions) were used to measure the motion angle and angular jerk cost of each task. Small accelerometers were attached at three locations: (1) the thoracolumbar vertebral transition area, (2) the lumbosacral vertebral transition area, and (3) the right thigh. The sensor at the thoracolumbar transition was placed with its upper edge aligned with that of the first lumbar vertebra, and the sensor at the lumbosacral transition was placed with its upper edge aligned with that of the sacrum. The thigh sensor was placed at the midpoint of the sciatic tubercle and the knee fossa on the posterior thigh. The two spinal column sensors were positioned at the midline of the body in the frontal plane and the thigh sensor was placed at the midline of the right thigh. The acceleration range was set to ±8 G, the angular velocity range to ±1.000 dps, and the sampling frequency to 100 Hz to acquire data on the sensor tilt angle in the sagittal plane. The lumbar spine motion angle was defined as the angle difference between the sensors at the thoracolumbar and lumbosacral transitions, and the hip motion angle was defined as the angle difference between the sensors at the lumbosacral and thigh transitions. Positive values of the motion angles for both the lumbar spine and hip joint were defined as motions in the flexion direction, whereas negative values were defined as motions in the extension direction. An increase in the angular jerk cost implied a rapid acceleration/deceleration of the joint, and the angular jerk cost was higher when the motion smoothness is low. The angular jerk cost was calculated from the tilt angle data of the two sensors, as described in a previous study (Table 1)[17]. Two trials were performed for each motor control task and the average of the two measurements was considered representative.

Pelvic tilt in the standing position was used to measure lumbar spine and hip mobility and motion smoothness during voluntary movement. The pelvic tilt task consisted of voluntary movement from a resting standing position with the upper limbs drooping to a maximal pelvic tilt backward/forward for 2 seconds and stopping at the final position for 2 seconds. Verbal instructions were given as follows: "Please tilt the pelvis posterior/anterior as much as possible without moving the thorax or knees". The motion angle was calculated as the average angle of the lumbar spine/hip for 1 second from 0.5 to 1.5 seconds after stopping at the final pelvic tilt position. The lumbar spine angular jerk cost, a measure of motion smoothness, was calculated as the average lumbar spine angular jerk cost for 1 second from 0.5 seconds to 1.5 seconds after the start of the pelvic tilt task (average angular jerk cost).

Catching the ball with eyes closed was used to evaluate reactivity to disturbances. The starting position was the standing position with eyes closed and holding the cage in contact with the chest. The examiner concealed the timing from the participants, dropped a 5 kg medicine ball into the cage from a height of 20 cm, and measured the lumbar spine motion angles. A small accelerometer was attached to the medicine ball, and the maximum value of the lumbar spine motion angle from the start to stop of the motion of the ball sensor was calculated.

The rocking four-point kneeling test was used to assess adaptive stability to prevent the lumbar spine from arising during upper and lower limb movements. The rocking task started with four-point kneeling with 90° shoulder and hip flexion, followed by voluntary movement to 120° hip flexion (rocking backward) or 60° hip flexion (rocking forward) for 2 s, and a 2-second stop at the final position. Verbal instructions were "Please move your buttocks backward/forward to avoid moving your low back as much as possible". The motion angle was calculated as the average angle of the lumbar spine during 1 second from 0.5 s to 1.5 s after stopping in the final position. The participant was informed of the final position when the hip angle was 60/120°, while the co-author measured the hip angle in real time.

The active joint repositioning sensation during lumbar flexion in the sitting position was used as an indicator of lumbar proprioception[18]. Active joint repositioning sense examines the difference from the correct position when the target position is reproduced with voluntary movements and its variability[19]. The lumbar flexion angle was defined as the tilt angle of the thoracolumbar transitional sensor and was evaluated using an iPhone inclinometer application[20]. The participants memorized the position where the lumbar flexion angle was 20° by flexing the trunk in a voluntary movement with the pelvis fixed from the position where the lumbar flexion angle was 0°, with their eyes closed, and the upper limbs crossed in front of the chest. The participants then again performed trunk flexion in voluntary movements, stopping at a position where they felt that the lumbar spine had moved by 20°. Measurements were taken three times, and the constant error (CE), absolute error (AE), and variable error (VE) were calculated from the measurements (Table 1)[19].

Trunk muscle strength was measured using hand-held dynamometry (μ-TasF1, ANIMA Inc., Tokyo, Japan), in accordance to a previous study[21] (Figure 2). The starting

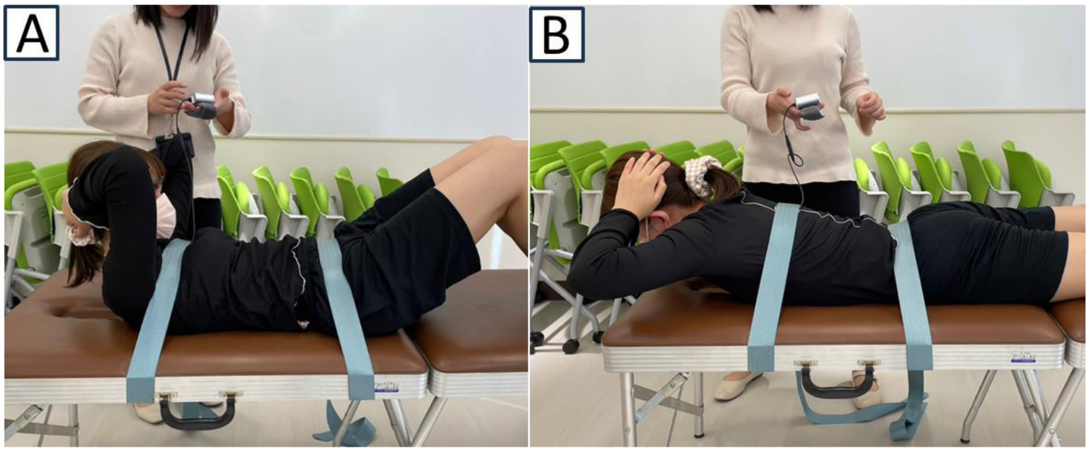

Figure 2. Measurement of trunk muscle strength. A: Trunk flexion, B: Trunk extension.

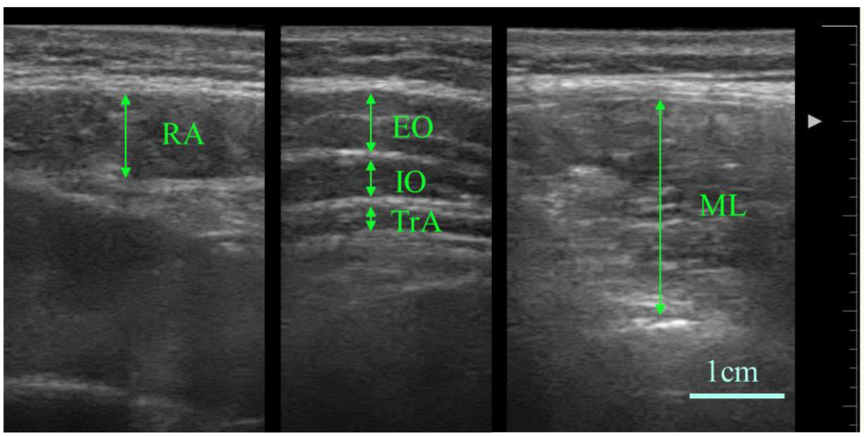

Figure 3. Measurement of muscle thickness using ultrasonography. RA: Rectus abdominis, EO: External oblique, IO: Internal oblique, TrA: Transverse abdominis, ML: Multifidus lumborum.

position for the measurement of trunk flexion muscle strength was the supine position with the lower limbs flexed and the upper limbs crossed behind the head. The handheld dynamometer was fixed with a belt at the height of the third intercostal space on the midline of the trunk and the pelvis was fixed to the bed with a belt on the anterior superior iliac spine. The starting position for the measurement of trunk extension muscle strength was the prone position with the upper limbs crossed behind the head. The handheld dynamometer was fixed with a belt at the height of the fifth thoracic vertebra on the midline of the trunk and the pelvis was fixed to the bed with a belt at the posterior superior iliac spine. The average of the two measurements for flexion and extension were used as representative values.

Muscle thickness was measured with a linear probe (10 MHz) in B-mode using an ultrasound imaging system (SONON, SAKAI Medical Co., Ltd., Tokyo, Japan). The right rectus abdominis, external oblique, internal oblique, transverse abdominis, and multifidus lumborum were measured. The thicknesses of the rectus abdominis, external oblique, internal oblique, and transverse abdominis muscles were measured in the supine position. The external and internal oblique and transversus abdominis muscles were measured according to the method described by Zamani et al.[22], with the center of the probe positioned at the midpoint of the costal margin and iliac crest on the right anterior axillary line, and a short-axis image was obtained. The rectus abdominis muscle was measured at the height at which the

Table 2. General characteristics of participants.

Characteristics	N= 25
Sex, N (%)	Male 12 (48.0)
	Female 13 (52.0)
Age (years)	21.9 (0.8)
Hight (cm)	165.4 (8.6)
Weight (kg)	57.7 (8.0)
BMI (kg/m^2)	21.0 (1.4)
Exercise time (min/week)	104.0 (145.9)

Values are presented as number of participants (%) or mean (standard deviation). BMI: body mass index.

Table 3. Lumbar motor control, lumbar proprioception, trunk muscle strength, and muscle thickness.

Motor control	**Pelvic tilt**	Posterior	Maximum angle *	Lumbar spine (deg)	7.3 (6.8)
				Hip (deg)	-5.5 (4.1)
			Average angular jerk cost (deg^2/sec^5)		1.6×10^7 (3.5×10^7)
		Anterior	Maximum angle *	Lumbar spine (deg)	-5.3 (4.3)
				Hip (deg)	6.0 (5.9)
			Average angular jerk cost (deg^2/sec^5)		6.5×10^6 (9.5×10^6)
	Ball catching	Lumbar spine angle (deg)			7.3 (3.7)
	Rocking	Lumbar spine angle in backward (deg)			9.2 (2.9)
		Lumbar spine angle in forward (deg)			−7.3 (4.1)
Active joint repositioning sense		CE (deg)			4.5 (2.7)
		AE (deg)			4.9 (2.1)
		VE (deg)			0.9 (0.6)
Muscle strength		Flexion (Kgf)			10.4 (5.3)
		Extension (Kgf)			11.0 (3.2)
Muscle thickness		RA (mm)			11.3 (1.9)
		EO (mm)			7.5 (2.1)
		IO (mm)			8.4 (2.8)
		TrA (mm)			2.9 (0.8)
		ML (mm)			28.2 (5.4)

*Values are presented as means (standard deviations). * Positive values for the motion angle imply motion in the flexion direction, and negative values imply motion in the extension direction. CE: Constant Error, AE: Absolute error; VE: Variable error; RA: Rectus abdominis; EO: External oblique; IO: Internal oblique; TrA: Transverse abdominis; ML: Multifidus lumborum.*

external and internal oblique and transversus abdominis muscles were measured and the maximum muscle thickness was measured. To measure the multifidus lumborum, the method described by Sions et al.[23] was used as a reference. The center of the probe was placed 2 cm to the right of the spinous process of the fourth lumbar vertebra in the prone position and a short-axis image was acquired. The muscle thickness between the fascia of each muscle was measured using the image analysis program ImageJ version 1.52 on the obtained images (Figure 3).

Statistical analysis

SPSS version 28 (IBM SPSS Statistics, Tokyo, Japan) was used for the statistical analysis. A partial correlation analysis was conducted to examine the relationship between the indicators of each motor control component using body mass index as a covariate. A multiple regression analysis (stepwise method) was used for factors related to each motor control component, with each item and body mass index as covariates. The significance level was set at $p<0.05$.

Table 4. Correlations among the components of lumbar motor control.

				Pelvic tilt					Ball catching	Rocking	
				Posterior		Anterior					
				Maximum angle	Average angular jerk cost	Maximum angle		Average angular jerk cost	Lumbar spine angle	Lumbar spine angle in backward	Lumbar spine angle in forward
				Hip		Lumbar spine	Hip				
Pelvic tilt	Posterior	Maximum angle	Lumbar spine	0.17 (0.42)	0.45 (0.03) [a]	−0.50 (0.01) [a]	−0.34 (0.10)	0.24 (0.25)	0.30 (0.15)	-0.02 (0.94)	0.38 (0.07)
			Hip		−0.04 (0.86)	0.23 (0.28)	−0.80 (<0.01)[a]	−0.21 (0.33)	0.33 (0.12)	−0.28 (0.19)	0.23 (0.28)
		Average angular jerk cost				−0.26 (0.23)	−0.05 (0.81)	0.58 (<0.01)[a]	0.15 (0.49)	0.01 (0.98)	0.42 (0.04)[a]
	Anterior	Maximum angle	Lumbar spine				0.01 (0.97)	−0.26 (0.22)	−0.20 (0.36)	−0.28 (0.19)	0.08 (0.72)
			Hip					0.05 (0.83)	−0.03 (0.16)	0.22 (0.30)	-0.32 (0.13)
		Average angular jerk cost							−0.12 (0.56)	−0.27 (0.19)	0.29 (0.17)
Ball catching		Lumbar spine angle								0.16 (0.46)	0.31 (0.14)
Rocking		Lumbar spine angle in backward									−0.37 (0.08)

Values are presented as correlation coefficients (p values). [a]Significant correlation (p<0.05).

Results

The general characteristics of the participants are shown in Table 2. The values of each measured item are shown in Table 3, and the correlations among the indicators of each component of motor control are shown in Table 4.

Partial correlation analysis of the indicators of motor control showed that the lumbar spine motion angle of the posterior pelvic tilt positively correlated (p=0.03, R=0.45) with the average angular jerk cost of the posterior pelvic tilt and negatively correlated (p=0.01, R=−0.50) with the lumbar spine motion angle of the anterior pelvic tilt. The hip motion angle of the posterior pelvic tilt was negatively correlated (p<0.01, R=−0.80) with the hip motion angle of the anterior pelvic tilt. The average angular jerk cost of the posterior pelvic tilt was positively correlated with the average angular jerk cost of the anterior pelvic tilt (p<0.01, R=0.58) and the rocking forward lumbar spine motion angle (p=0.04, R=0.42).

Table 5 presents the results of the multiple regression analysis. When the lumbar spine motion angle of the posterior pelvic tilt was the dependent variable, VE (β=0.44, p=0.02) and trunk flexion muscle strength (β=0.37, p=0.05) were significantly related factors. When the hip motion angle of the posterior pelvic tilt was the dependent variable, AE (β=0.44, p=0.03) was identified as a significantly associated factor. When average angular jerk cost of pelvic anterior tilt was used as the dependent variable, rectus abdominis muscle thickness (β=0.41, p=0.04) was a significant associated factor. When the lumbar spine motion angle in ball catching was used as the dependent variable, rectus abdominis muscle thickness (β=0.43, p=0.03) was a significant associated factor. When lumbar spine motion angle of rocking forward was the dependent variable, AE (β=0.50, p=0.01) was a significant associated factor. The variance inflation factors were less than 10 for all items, and there was no multicollinearity among the independent variables.

Discussion

This study investigated the relationship between the indicators of each component of lumbar motor control and factors related to the indicators of each component of lumbar motor control.

In the present study, lumbar spine and hip motion angles and average angular

Table 5. Factors associated with lumbar motor control.

			Partial regression coefficient (B)	Standard partial regression coefficient (β)	p-value	95% Confidence interval	Variance inflation. Factor
Pelvic tilt	Posterior (Lumbar spine maximum angle)	VE	5.06	0.44	0.02	0.96 to 9.16	1.01
		Flexion muscle strength	0.47	0.37	0.05	0.01 to 0.92	1.01
		Adjusted R^2			0.30		
	Posterior (Hip maximum angle)	AE	0.88	0.44	0.03	0.11 to 1.65	1.00
		Adjusted R^2			0.16		
	Anterior (Average angular jerk cost)	RA muscle thickness	2.09×10^7	0.41	0.04	7.40×10^5 to 4.10×10^7	1.00
		Adjusted R^2			0.13		
Ball catching (Lumbar spine angle)		RA muscle thickness	0.59	0.43	0.03	0.05 to 1.13	1.00
		Adjusted R^2	0.15				
Rocking forward (Lumbar spine angle)		AE	1.00	0.50	0.01	0.25 to 1.74	1.00
		Adjusted R^2			0.21		

AE: Absolute error, VE: Variable error, RA: Rectus abdominis, EO: External oblique.

jerk costs were correlated with the posterior and anterior pelvic tilts. Therefore, it is suggested that the magnitude and smoothness of motion are related, even if the direction of motion is opposite for the same task. Pelvic morphological features and pelvic incidence determine the mobility of structural pelvic tilt[24]. Therefore, when the pelvic incidence is high, the pelvis has greater mobility in both the posterior and anterior tilt directions, whereas when the pelvic incidence is low, the pelvis has less mobility in both the posterior and anterior tilt directions. Miyachi et al.[25] reported that the magnitude of motion in the lumbar spine flexion and extension directions differed between those with low back pain during flexion and those with low back pain during extension. Although our findings imply that the magnitude and smoothness of lumbar spine and hip motion were related even when the direction of motion was reversed because participants without significant pain or functional impairment were included in this study, the present results may have been different if another factor caused the effects before the structural limitation was reached.

No significant correlations were found between the indicators of each motor control component, except for the average angular jerk cost of the pelvic posterior tilt and lumbar spine motion angle of rocking forward. Thus, the results support the hypothesis that each component of lumbar motor control is independent of the other components. Movement is controlled not only by the activity of agonistic muscles but also by the activity of other muscles including antagonistic muscles[26-28]. However, the amount of muscle activity and feedback required for a task in which the lumbar spine is stopped by co-contraction of the agonist and antagonist muscles differs from a task in which the antagonist muscles coordinate their movements in response to agonist muscle activity. Similarly, neuromuscular recruitment is different for the tasks of stopping quickly and maintaining a stop in conjunction with slow movement[29]. Therefore, it is not surprising that indicators of motor control are not interrelated when the components of motor control differ across tasks, as observed in the present study. Because one component of lumbar motor control alone cannot be interpreted with respect to other components, we consider it necessary to evaluate lumbar motor control in clinical situations by considering the components of lumbar motor control for which the function is required.

AE was identified as a factor related to the hip motion angle in posterior pelvic tilt and the lumbar motion angle in forward rocking, whereas VE was a factor related to the lumbar motion angle in posterior pelvic tilt. Sensory information is essential for motor control because motor control output is adjusted based on the sensory information obtained[15,30]. In this study, lumbar motor control was related to lumbar proprioception, and it is important to evaluate lumbar proprioception when evaluating lumbar motor control. Furthermore, the rectus abdominis muscle thickness was identified as a relevant factor in the lumbar spine motion angle in ball catching and the average angular jerk cost in anterior pelvic tilt. The rectus abdominis is an antagonistic muscle in terms of the direction of motion during ball catching and anterior pelvic tilt. However, as mentioned above, motor control requires control by antagonistic muscles[26-28], and based on our results, it is possible that the rectus abdominis muscle, which is an antagonistic muscle for lumbar extension was also relevant to motor control. However, it is interesting to note that in the present study, deep abdominal muscles, such as the transversus abdominis and internal oblique muscles[31,32], which have been discussed as muscles related to trunk stability in many studies, did not appear to be related to motor control. The transversus abdominis and internal oblique muscles are considered to contribute to the overall stability of movement rather than direction-specific activity such as the rectus abdominis[33]. In addition, the cessation of trunk movement requires the overall activity of all muscles, not just a single muscle[34]. Furthermore, motor control does not necessarily require maximum muscle strength which is affected by the muscle cross-sectional area[35]. In fact, in the present study, maximal muscle strength was not identified as a relevant factor in any task, except for the lumbar spine movement angle in the posterior pelvic tilt. Therefore, muscles such as the transversus abdominis which do not require direction-specific activity, might have had a smaller effect on indicators of motor control in this study. These results suggest that it is necessary to evaluate both agonistic and antagonistic muscles when evaluating parameters related to muscle size (such as muscle thickness and cross-sectional area).

One limitation of this study is that the participants were young and healthy. Given that the results may differ for those with pain and functional disabilities, it is necessary to validate these results in other populations and clarify the characteristics of each component of motor control in each population. Several factors that could be related to motor control were investigated in this study; however, factors related to lumbar hip motion as listed by Zawadka et al.,[36] including hamstring stiffness, movement speed, and muscle fatigue, were not investigated in this study under different conditions or under the influence of other joints. In particular, muscle activity has not been examined using electromyography; therefore, the degree and timing of muscle activity remain unclear, and further research using other factors and conditions are necessary.

Conclusions

This study verified the relationship between the indicators of each component of the lumbar motor control and the factors related to the indicators of each component. The indicators for each component of the lumbar motor control were independent and must be evaluated for the components whose functions are required. In addition, some components of lumbar motor control are related to lumbar proprioception and thickness of the rectus abdominis muscle which are important for evaluating lumbar motor control.

Ethics approval

This study was approved by the Ethics Committee of our institution (approval date: July 28, 2023; Approval No. 2023-19). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent to participate

The purpose and methods of this study were explained orally and in writing, and written consent for "free participation" was obtained from participants before the study was conducted.

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