Journal of Human Kinetics volume 50/2016, 53 - 62 DOI: 10.1515/hukin-2015-0141
Section I – Kinesiology

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Three-Dimensional Motion Analysis of Lumbopelvic Rhythm During Trunk Extension

by

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Hip–spine coordination, known as the lumbopelvic rhythm, can be expressed as the lumbar–hip ratio. The lumbopelvic rhythm and lumbar–hip ratio can be used to assess lower limb function. We clarified the lumbopelvic rhythm and lumbar–hip ratio during trunk extension. We established a novel set of marker positions for three-dimensional motion analysis to assess the lumbar spinal angle. The original markers were placed on both paravertebral muscle groups at the 11th thoracic spinous process level, the 10th and 12th thoracic spinous processes, and the pelvis. We measured angle data during trunk extension using three-dimensional motion analysis, and the data for eight healthy male subjects were categorized into backward and forward phases. The lumbar–hip ratio increased significantly from 1.2 to 1.9 (mean, 1.6) in the backward phase, indicating considerable movement of the lumbar spine compared with hip movement in the latter phase. In the forward phase, the ratio decreased significantly from 1.9 to 0.5 (mean, 1.5). After completion of 80% of the forward phase, the lumbar–hip ratio decreased to <1.0. The lumbopelvic rhythm for trunk extension was better expressed by a cubic or quadratic function than a linear function. According to a linear function, when the hip extends by 1°, lumbar spine extends by 1.9°. Therefore, lumbar spinal movement was greater than hip movement in the sagittal plane. The implication of the curved line would indicate lumbar extension instead of the limitation of hip extension.

Key words: *lumbopelvic rhythm, lumbar–hip ratio, lumbar spine angle, hip angle, trunk extension.*

Introduction

Hip and spine coordination, which is known as the lumbopelvic rhythm (LPR), is similar to the scapulohumeral rhythm during shoulder movement. Concurrent movement of the scapula and humerus is an important component of arm function (Inman et al., 1944; McQuade et al., 1995). Likewise, concurrent movement of the hip and lumbar spine contributes to the locomotor function of the lower limbs (Esola et al., 1996; McClure et al., 1997; Wong and Lee, 2004). The LPR can be expressed as the lumbar–hip ratio (LHR), which represents the ratio of lumbar range of motion (ROM) to hip ROM. A LHR greater than 1.0 indicates that lumbar motion is greater than hip motion, and a LHR less than 1.0 indicates that lumbar motion is lesser than hip motion.

Several studies have evaluated the LHR in trunk flexion, but not in trunk extension. Esola et al. (1996) studied trunk flexion, dividing it into three phases of 0–30°, 30–60°, and 60–90° and reporting LHR values of 1.6, 1.1, and 0.5, respectively. Mayer et al. (1984) also studied trunk flexion, dividing it into two phases of 0–90° and 90–120° and reporting LHR values of 1.7 and 0.2, respectively. McClure et al. (1997) studied trunk extension from the maximum flexion position to a

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Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 50/2016 in March 2016.

neutral position, dividing it into four phases of 0–25%, 25–50%, 50–75%, and 75–100% and reporting LHR values of 0.2, 0.6, 0.9, and 3.0, respectively. Therefore, the reported values of LHR are 0.2–3.0 during trunk flexion (Esola et al., 1996, Mayer et al., 1984; McClure et al., 1997) and 1.4 at maximum trunk extension (Wong and Lee, 2004). These studies suggested that the LHR changed during sagittal motion, however, did not explain the reason of this change. Furthermore, these previous studies did not report the change in the LHR or in the angle of the lumbar spine and hip during trunk extension and did not use three-dimensional (3D) motion analysis with more precision.

Many reports for lumbar ROM during trunk extension resulted in inconsistent findings because of variation in subjects' ages, postures, and devices. Burton (1986) used hydrogoniometry in the prone position and reported a lumbar ROM of 36.4°, whereas Pearcy et al. (1985) used radiography for subjects aged 25–36 years in the standing position and reported a lumbar ROM of 19°. Dopf et al. (1994) used the CA–6000 Spine Motion Analyzer and Inclinometer in subjects aged 20–35 years in the standing position and reported lumbar ROM values of 32° and 19°, respectively. Wong and Lee (2004) used a 3SPACE Fastrak in subjects aged 42 years in the standing position and reported a lumbar ROM of 15.5°.

Based on reports for scapulohumeral rhythm (Inman et al., 1944; McQuade et al., 1995), we evaluated the LPR using a graph with the hip angle plotted along the x-axis and the lumbar spine angle plotted along the y-axis. If the LPR is appropriate for a linear function, the LHR would not change. However, if the LHR changes during trunk extension, then as the ratio of these variables, the LPR cannot be expressed by a linear function. To date, no study has reported the values of the LPR during trunk extension.

To clarify the LPR and LHR during trunk extension, we used 3D motion analysis. We hypothesized that the LPR would not show a linear trend as the LHR changes during trunk extension as previously reported for trunk flexion. We also assumed that normal reference values of the LPR and LHR would be useful for the assessment of abnormal values.

The medical implication of clarifying the LPR and LHR by 3D motion analysis would be a useful tool for assessing lumbar movement in patients with spinal/hip disorders such as hip–spine syndrome (Offierski and Macnab, 1983). It allows us to assess lower limb and spinal malfunction according to deviation from normal ranges of LPR and LHR values.

Material and Methods

Participants

We recruited eight male volunteers (mean ± SD; age, 33.3 ± 5.4 years; body height, 173.1 ± 6.0 cm; body mass, 67.7 ± 7.8 kg; body mass index: 22.6 ± 1.9 kg/m2). The criteria for inclusion were as follows: no significant back pain in the previous year, no prior spinal surgery, no prior disability due to back pain, no obvious spinal deformities, and no pain in the joints of the lower extremities. After the protocol for this study was approved by the Institutional Ethics Committee Board at the Faculty of Medicine, the University of Tokyo (approval no. 3614), informed consent was obtained from all subjects.

Measures

We used a 3D motion analysis system (VICONMX, VICON Motion Systems Ltd., Oxford, UK) with seven cameras and two force plates (AMTI OR6, Advanced Mechanical Technology, Inc., Watertown, MA). Based on previously reported methodology (Tojima et al., 2013), seven original spherical markers, 14 mm in diameter, were placed on the following anatomical landmarks: right and left posterior superior iliac spines (PSISs) and right and left paravertebral muscles at the 11th thoracic vertebra (T11), T10, T12, and the third sacral vertebra (S3) (Supplement 1). In comparison with plug-in-gait model marker sets (Davis et al., 1991), the merits of original marker sets allowed us to calculate the detailed lumbar spine angle as four markers were placed on the thoracolumbar area. Furthermore, plug-in-gait model markers were placed over the subject's whole body. Spherical marker trajectories and ground reaction forces were recorded during trunk extension at 100 Hz and 1 kHz, respectively, using the 3D motion analysis system.

Procedures

Subjects were asked to perform trunk extension four times. Trunk extension took 16 s and was measured on the basis of the rhythm of a metronome (ME-110, Yamaha Corp., Japan). We asked the subjects to stand in a neutral position for the first 4 s, to extend the lumbar spine to the maximal point for the next 4 s, to return to the neutral position for the subsequent 4 s, and to stand in the neutral position for the final 4 s.

Data analysis

The signals from the marker trajectories and ground reaction forces during trunk motion were filtered conventionally with a fourth-order zero-phase Butterworth filter with two low-pass filters (a 6-Hz filter for marker trajectories and a 16-Hz filter for ground reaction forces) to eliminate noise from the raw data. From the Plug-in-gait markers, we used the Vicon Body Builder 3.6.1 (VICON Motion Systems Ltd., Oxford, UK) to measure hip ROM, the center of mass (COM) for the whole body, waist (lumbar) and hip moment, and lumbar and hip power. We used the COM, joint moment, and joint power data to calculate values of the LPR and LHR.

The thoracolumbar segment was defined using markers located at T10 and T12 as well as the two paravertebral markers at T11. The pelvic segment was defined using markers located on S3 and both PSISs. Lumbar motion was defined as the movement of the thoracolumbar segment with respect to the pelvic segment (i.e., the sum of L1–5 vertebral movements). A joint coordinate system convention (Crosbie et al., 1997; Tojima et al., 2013) was used to compute angle data, and data with negative values were changed to positive values.

We calculated the LHR as the ratio of lumbar ROM to the average of right and left hip ROM (Esola et al., 1996; McClure et al., 1997) and normalized the COM and joint moment according to the subjects' height and body mass, respectively. We used the average of moment and power data for the right and left hip. Since the LHR would approach infinity with a hip ROM of 0–1°, we used hip ROM to define trunk extension. We defined the start of extension as the point when the hip ROM was ≥1° and the end of extension as the point when the hip ROM was ≤1°. We separated the data into two phases according to hip ROM: the backward phase (from the start to the mean maximum hip angle) and the forward phase (from mean maximum hip ROM to the end). After normalizing both phases to 100% using MATLAB (MathWorks, Natick, MA), we statistically analyzed 10% intervals of the LHR. Accordingly, the COM, lumbar and hip moment, and lumbar and hip power were divided between the two phases and normalized to 100%.

Statistical analysis

We used IBM SPSS Statistics ver. 19.0 (International Business Machines Corporation, Endicott, NY). One-way repeated measures analysis of variance was employed to analyze each 10% interval of the LHR. The Tukey's (honestly significant difference) post hoc test was used to test significant effects, and curve estimation (linear, quadratic, or cubic function) was used to describe the LPR. The level of significance was set at $p < 0.05$.

Results

Maximum values of ROM, the LHR and LPR

The mean maximum hip ROMs of the left and right sides and the average of both were 17.3°, 16.9°, and 17.1°, respectively. The mean maximum lumbar ROM was 30.1° (Figure 1).

In the backward phase, the LHR significantly increased from 1.2 (at 8% time) to 1.9 (at 88% time) [$F(10, 70) = 9.352$, $p < 0.001$], with an average over the total phase of 1.6 (Table 1). This indicates that lumbar spinal movement was greater than hip movement during the backward phase. In the forward phase, the LHR significantly decreased from 1.9 (at 8% time, or 92% time for the backward phase) to 0.5 (at 96% time, or 4% time for the backward phase) [$F(10, 70) = 2.965$, $p = 0.004$] and was <1.0 after 80% time (at 20% time for the backward phase), with an average over the total phase of 1.5 (Table 2). This indicates that lumbar spinal movement was more reduced than hip movement during the forward phase (Figure 2).

The LPR was described using three formulae during the backward phase (linear function, $y = 1.9x - 3.5$, $R2 = 0.982$, $p < 0.001$; quadratic function, $y = 0.058x2 + 0.746x + 0.724$, $R2 = 0.998$, $p < 0.001$; and cubic function, $y = -0.0017x3 + 0.108x2 + 0.3361x + 1.5082$, $R2 = 0.998$, $p < 0.001$; $1.0° \le x \le 17.1°$) as well as during the forward phase (linear function, $y = 1.9x - 3.0$, $R2 = 0.997$, $p < 0.001$; quadratic function, $y = 0.017x2 + 1.558x - 1.832$, $R2 = 0.998$, $p < 0.001$; and cubic function, $y = -0.0014x3 + 0.0565x2 + 1.2517x - 1.2493$, $R2 = 0.999$, $p < 0.001$; $1.0° \le x \le 17.1°$), where y and x are the lumbar ROM and hip ROM, respectively (Figure 3). These linear functions indicate that when the hip extends 1°, the lumbar spine extends 1.9°.

Joint moment

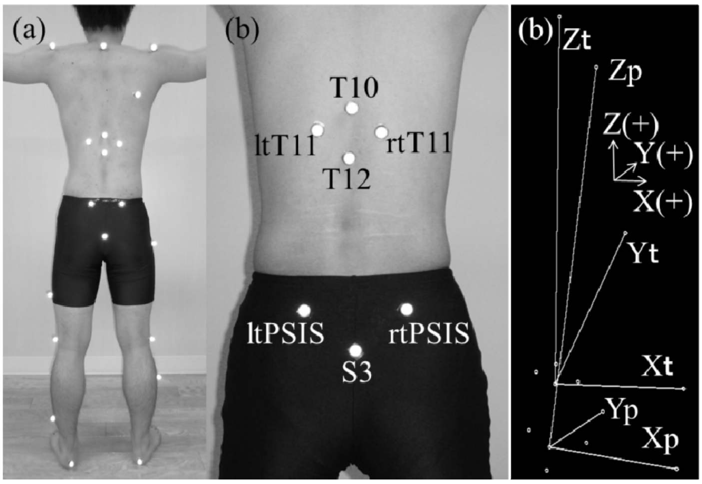
The flexor moment for the hip and lumbar spine increased in the backward phase (Supplement 2). The mean maximum hip flexion moment (Nm/kg) for the left side, right side, and both sides averaged were 0.33, 0.44, and 0.39, respectively. The mean maximum lumbar flexion moment was 0.77.

Joint power

Joint power measurements indicated that abdominal muscles and hip flexor muscles contracted eccentrically in the backward phase and concentrically in the forward phase (Supplement 3).

Center of mass

The mean maximum shift of the COM position (%height) was 4.0 posteriorly and 3.5 inferiorly (Supplement 4). After 80% time in the forward phase (12% time for the backward phase), the COM remained in the posteroinferior position in comparison with the backward phase.



Supplement 1

*(**a**) Location of plug-in gait markers with original markers (view from posterior), (**b**) Location of original markers (view from posterior) and (**c**) orientation of the anatomical segments of the pelvis (p) and thoracolumbar (t) segments in the three-dimensional motion analysis (view from right posterior oblique)*

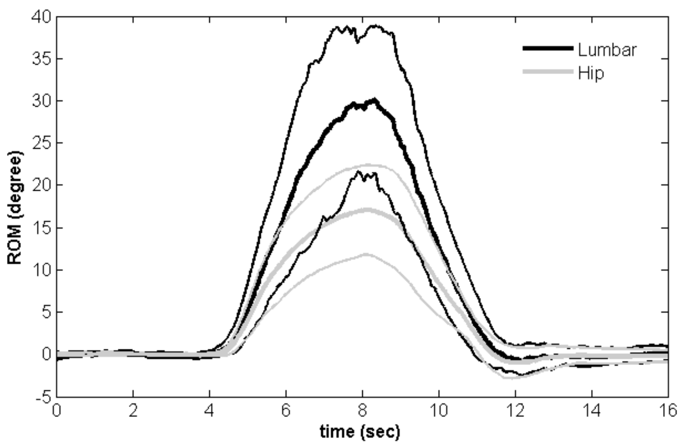


Figure 1

The mean (thick lines) and standard deviation (SD; thin lines) of lumbar range of motion (ROM; black) and hip ROM (gray)

Table 1

Tukey's honestly significant difference test results for the LHR in the backward phase

%time		*p*	95% confidence interval lower	upper	%time		*p*	95% confidence interval lower	upper
0	10	0.934	−0.193	0.486	30	40	0.988	−0.453	0.225
	20	1.000	−0.285	0.394		50	0.344	−0.591	0.088
	30	1.000	−0.362	0.317		60	0.061	−0.671	0.008
	40	0.958	−0.476	0.203		70	0.016	−0.720	−0.041
	50	0.227	−0.613	0.065		80	0.023	−0.707	−0.028
	60	0.033	−0.694	−0.015		90	0.003	−0.773	−0.094
	70	0.008	−0.742	−0.064		100	0.007	−0.748	−0.070
	80	0.012	−0.730	−0.051	40	50	0.957	−0.477	0.202
	90	0.001	−0.796	−0.117		60	0.559	−0.557	0.122
	100	0.003	−0.771	−0.093		70	0.263	−0.606	0.073
10	20	0.998	−0.431	0.247		80	0.328	−0.593	0.085
	30	0.850	−0.509	0.170		90	0.082	−0.659	0.020
	40	0.188	−0.623	0.056		100	0.146	−0.634	0.044
	50	0.005	−0.760	−0.081	50	60	0.999	−0.419	0.259
	60	0.000	−0.840	−0.161		70	0.972	−0.468	0.210
	70	0.000	−0.889	−0.210		80	0.986	−0.456	0.223
	80	0.000	−0.877	−0.198		90	0.782	−0.522	0.157
	90	0.000	−0.942	−0.264		100	0.898	−0.497	0.182
	100	0.000	−0.918	−0.239	60	70	1.000	−0.388	0.290
20	30	1.000	−0.417	0.262		80	1.000	−0.376	0.303
	40	0.730	−0.531	0.148		90	0.995	−0.442	0.237
	50	0.066	−0.668	0.011		100	1.000	−0.417	0.262
	60	0.007	−0.748	−0.069	70	80	1.000	−0.327	0.352
	70	0.001	−0.797	−0.118		90	1.000	−0.393	0.286
	80	0.002	−0.785	−0.106		100	1.000	−0.368	0.311
	90	0.000	−0.850	−0.172	80	90	1.000	−0.405	0.273
	100	0.000	−0.826	−0.147		100	1.000	−0.381	0.298
					90	100	1.000	−0.315	0.364

Table 2

Tukey's honestly significant difference test results for the LHR in the forward phase

%time		p	95% confidence interval		%time		p	95% confidence interval	
			lower	upper				lower	upper
100	90	1.00	−1.34	1.23	70	60	1.00	−1.29	1.28
	80	1.00	−1.32	1.24		50	1.00	−1.29	1.28
	70	1.00	−1.23	1.33		40	1.00	−1.22	1.35
	60	1.00	−1.24	1.33		30	1.00	−1.13	1.44
	50	1.00	−1.24	1.33		20	0.57	−0.47	2.10
	40	1.00	−1.17	1.40		10	0.18	−0.20	2.36
	30	1.00	−1.07	1.49		0	0.22	−0.24	2.33
	20	0.48	−0.42	2.15	60	50	1.00	−1.28	1.28
	10	0.13	−0.15	2.41		40	1.00	−1.21	1.35
	0	0.17	−0.19	2.38		30	1.00	−1.12	1.45
90	80	1.00	−1.26	1.30		20	0.56	−0.46	2.11
	70	1.00	−1.17	1.39		10	0.18	−0.20	2.37
	60	1.00	−1.18	1.39		0	0.21	−0.24	2.33
	50	1.00	−1.18	1.39	50	40	1.00	−1.21	1.35
	40	1.00	−1.11	1.46		30	1.00	−1.12	1.45
	30	1.00	−1.02	1.55		20	0.56	−0.46	2.11
	20	0.38	−0.36	2.21		10	0.18	−0.20	2.37
	10	0.09	−0.10	2.47		0	0.21	−0.24	2.33
	0	0.12	−0.13	2.43	40	30	1.00	−1.19	1.38
80	70	1.00	−1.19	1.37		20	0.68	−0.53	2.04
	60	1.00	−1.20	1.37		10	0.25	−0.27	2.30
	50	1.00	−1.20	1.37		0	0.30	−0.31	2.26
	40	1.00	−1.13	1.44	30	20	0.83	−0.62	1.94
	30	1.00	−1.03	1.53		10	0.39	−0.36	2.20
	20	0.41	−0.38	2.19		0	0.45	−0.40	2.17
	10	0.11	−0.11	2.45	20	10	1.00	−1.02	1.55
	0	0.13	−0.15	2.42		0	1.00	−1.06	1.51
					10	0	1.00	−1.32	1.25

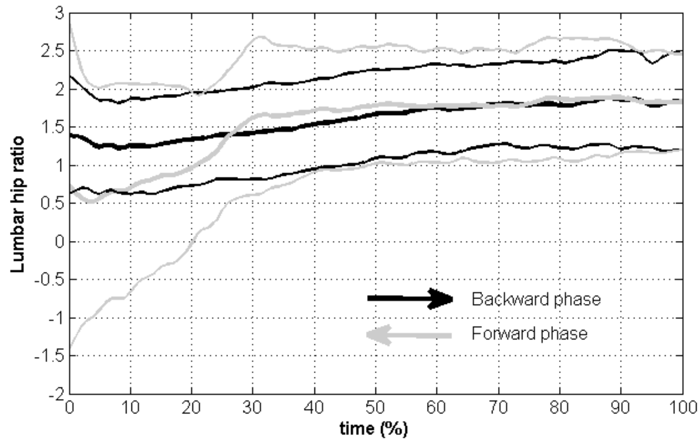


Figure 2

The mean (thick lines) and standard deviation (SD; thin lines) of the lumbar–hip ratio during the backward phase (black) and the forward phase (gray) of trunk extension

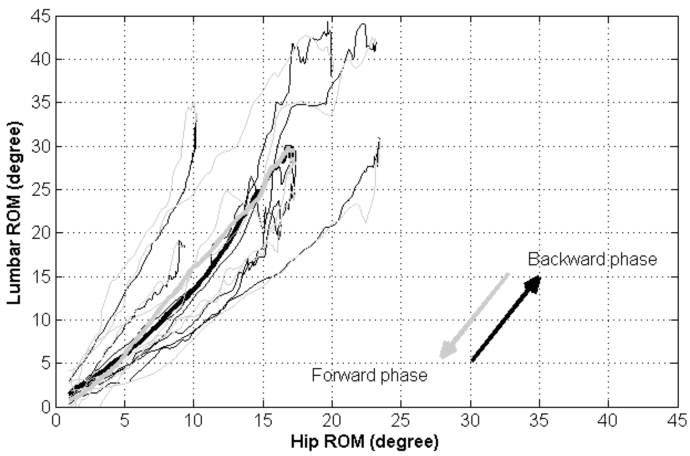
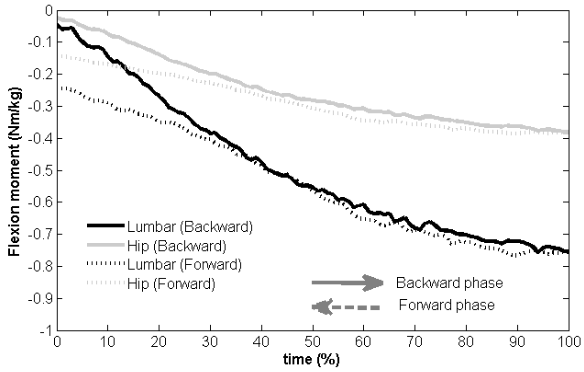


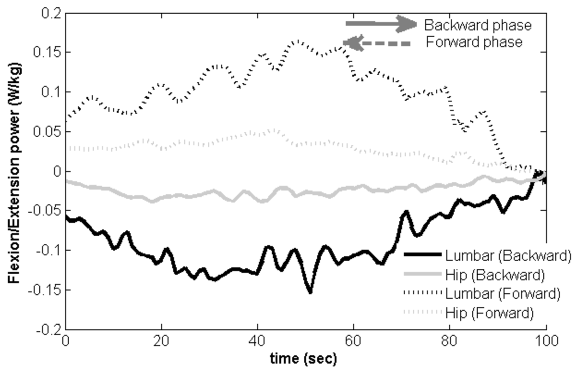
Figure 3

The mean (thick lines) and individual data (thin lines) for the lumbopelvic rhythm during the backward phase (black) and forward phase (gray) of trunk extension. ROM, range of motion



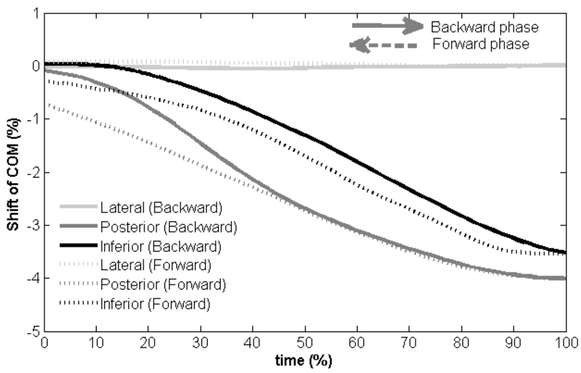
Supplement 2

The mean lumbar moment (black) and hip moment (gray) during the backward phase (unbroken lines) and the forward phase (broken lines) in flexion (−)/extension (+) axis



Supplement 3

The mean lumbar power (black) and hip power (gray) during the backward phase (unbroken lines) and the forward phase (broken lines) in flexion/extension. Negative values indicate eccentric muscle contraction, and positive values indicate concentric muscle contraction.



Supplement 4

Shift of the mean center of mass (COM) during the backward phase (unbroken lines) and the forward phase (broken lines). Negative values indicate a leftward, posterior, or inferior shift of the COM

Discussion

Our results for lumbar ROM were comparable with previous studies that reported maximum lumbar ROM for healthy male subjects during trunk extension. The lumbar ROM of 30.1° observed in the present study is comparable to that reported by Dopf et al. (1994). Furthermore, Wong and Lee (2004) reported a maximum hip ROM of 15.7°, which is comparable to our result of 17.1°.

Our novel marker set with the plug-in gait marker set for measuring the lumbar angle by 3D motion analysis could assess the LHR during trunk extension. Wong and Lee (2004) studied trunk extension from the neutral position and reported an LHR of 1.4, but they did not report the changes in the LHR. In the present study, the average change in the LHR was 1.6. Our result is comparable to that of Wong and Lee (2004). Therefore, lumbar spinal movement was greater than hip movement in the sagittal plane.

We found that the LPR could be better represented by a quadratic or cubic function than a linear function during trunk extension in both phases. If the LPR could be described by a linear function, then the LHR would not change. However, our results showed the change of the LHR, which indicates that the LPR cannot be accurately described by a linear function. In short, very small coefficients of quadratic and cubic functions for the LPR influence the changes in the LHR. The implication of the curved line would indicate lumbar extension instead of the limitation of hip extension. When the angle of trunk extension was increased, the angle of lumbar extension would be increased instead of the limitation of hip extension. This relationship between lumbar and hip movement during trunk extension would indicate the curved line.

Furthermore, we can explain trunk extension using two strategies. The first strategy involves the maintenance of balance mainly achieved by contracting the abdominal muscles eccentrically in the backward phase. In this phase, the LHR was >1.0, indicating that lumbar spinal movement was greater than hip movement under a well-balanced position in this phase. In our study, the power values for the lumbar spine and hip were negative, indicating that subjects contracted their abdominal and hip flexor muscles eccentrically. The COM shifted posteroinferiorly, and the flexion moment for the lumbar spine was more than twice that for the hip, because subjects maintained the backward position by using their abdominal muscles more than the hip flexors. Previous studies also reported that subjects used the abdominal muscles more than the hip flexors to maintain a well-balanced position (Horak and Nashner, 1986; Nashner, 1982).

The second strategy involves the use of hip flexor muscles for fine control of the upright position in the late forward phase. In the forward phase, a strategy opposite to that used in the backward phase would lead to a decrease in the LHR, making most of the results overlap with the backward phase results. In comparison with the backward phase, the COM remained posteroinferior and the LHR was <1.0 after 80% extension in the forward phase. In this phase, the subject used mainly the hip flexor muscles to control the upright position, which could lead to an LHR value of <1.0.

The limitation of this study is that the LPR and LHR were assessed using only the motion of the lumbar spine and hip during trunk extension. Further studies of other joints and muscle functions are needed to explain the LPR and LHR. Moreover, we could only analyze 8 participants' data. Not only a large number of male as well as female participants, but the change of the load for the trunk or the movement speed would have generalized the LPR and LHR.

In clinical implications, the LPR and LHR with our maker set would be able to assess the rehabilitation effect for patients with low back pain and to estimate the precise lumbar ROM during trunk motion in many conditions such as after surgery for scoliosis patients or spinal fusion. Furthermore, if a patient with low back pain and no spinal malfunction shows an LPR or LHR outside of the normal ranges, the cause of pain could be hip malfunction (i.e., hip osteoarthritis). In such cases, rehabilitation for hip malfunction could improve low back pain due to hip–spine syndrome, which would also improve the LPR and LHR.

We believe that the LPR and LHR measurement proposed in this study will allow athletes and coaches to assess the substantial training effects of trunk extension especially in the context of competitive sports. More specifically, the measurement method enables us to research the precise lumbar ROM during trunk motion often observed in the practice of gymnastics such as on a balance beam or floor exercise.

Acknowledgements

We presented part of this study (lumbopelvic rhythm and lumbar–hip ratio data) in an oral session at the 7th World Congress of the International Society of Physical and Rehabilitation Medicine (ISPRM), which was held in Beijing, China from June 16–20, 2013.

Funding: This study was supported in part by research grants from JSPS KAKENHI (Grant No. 25282159), the General Insurance Association of Japan, the Japanese Hip Research Foundation, and the Japanese Society for Musculoskeletal Medicine.

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