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Original Article

Three-dimensional motion analysis of lumbopelvic rhythm during lateral trunk bending

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Abstract. [Purpose] To examine the variations in the lumbopelvic rhythm and lumbar-hip ratio in the frontal plane. [Subjects and Methods] Markers were placed on the T10 and T12 spinous processes, bilateral paravertebral muscles at the T11 level, the pelvis, and the femur. Lumbar spine and hip angles were measured during lateral trunk bending using three-dimensional motion analysis. Data from the trunk lateral bending movement were categorized into descending (start of hip movement to when the hip angle reached its maximum value) and ascending (from the maximum hip angle to the end of movement) phases. The lumbar-hip ratio was calculated as the ratio of the lumbar spine angle to the hip angle. [Results] The lumbar-hip ratio decreased from 5.9 to 3.6 in the descending phase, indicating lumbar spinal movement was less than hip movement. In the ascending phase, the lumbar-hip ratio was reversed. The lumbopelvic rhythm was better expressed by a cubic or quadratic function rather than a linear function. These functions indicate that when the hip inclines by 1° that the lumbar spine bends laterally by 2.4°. [Conclusion] The lumbopelvic rhythm and lumbar-hip ratio indicate lumbar lateral bending instead of a limitation of hip inclination.

Key words: Lumbopelvic rhythm, Lumbar-hip ratio, Trunk lateral bending

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INTRODUCTION

The coordination between the lumbar spine and hip during trunk motion is known as the lumbopelvic rhythm (LPR), which is similar to the scapulohumeral rhythm during arm elevation in the scapular plane that indicates upper limb function[1)]. Like the scapulohumeral rhythm, the LPR indicates lower limb function during trunk motion[2–5)]. The LPR has been also calculated as the lumbar-hip ratio (LHR: lumbar angle/hip angle[2, 3)]). An LHR ≥1.0 indicates that lumbar motion is greater than hip motion. The LHR has been reported at the position of maximum flexion[2)], extension[3)], and lateral bending of the trunk[4)]. On the basis of previous reports regarding the LPR[5)], the LPR was evaluated using a graph with the hip joint angle plotted along the x-axis and the lumbar spine angle plotted along the y-axis. If the LHR changes, the LPR cannot be appropriately described by a linear function. However, there are no previous studies that measured the change in LHR during lateral bending or made use of the increased precision of three-dimensional (3D) motion analysis. Similarly, it has not been reported how joint moment and joint power are used to maintain well-balanced posture during lateral trunk bending.

There are many reports of the maximum angle of the lumbar spine during lateral bending in healthy participants from a standing position. Some studies have investigated the maximum lumbar angle during lateral bending radiographically in healthy standing participants. Pearcy and Tibrewal[6)] found a maximum angle of 18°, Dvorak et al.[7)] found 29°, and Wong and

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Lee[4] using 3SPACE Fastrak found a maximum angle of 24°.

Humans control their body balance while standing like inverted pendulums[8, 9]. Strategies involving the hip and ankle are used to keep balance. Postural control is not reflexive but rather a coordination of lower limb motion that is thought to be under central nervous system control[9–11]. Previous studies have shown that humans voluntarily stabilize the center of mass (COM) of their whole body to maintain balance during perturbation. The COM is located anterosuperior to the pelvis[9]. Therefore, the lumbar spine and hip have important functions in stabilizing the COM.

The load to the lumbar spine, leg muscle tightness[12], and lower back pain[13] have been shown to increase the activity of the lumbar erector spinae and decrease hip movement. Examining the LPR and LHR using 3D motion analysis provides a useful tool for assessing lumbar and hip movement in patients with spinal/hip disorders such as lower back pain and scoliosis.

The purpose of this study was to clarify the LPR and LHR during lateral trunk bending. The COM, joint moment, and joint power data were used to describe the values of the LPR and LHR as supplementary data. Our hypothesis was that the LPR and LHR during lateral trunk bending could assess locomotor function of the spine and lower limb.

SUBJECTS AND METHODS

Eight male volunteers (age: 33.3 ± 5.4 years, height: 173.1 ± 6.0 cm, weight: 67.7 ± 7.8 kg, BMI: 22.6 ± 1.9 kg/m^2) were recruited. Inclusion criteria were as follows: no significant back pain in the previous year and no painful joints in the lower extremities. The study protocol was approved by the institutional ethics review board of the University of Tokyo (No. 3614), and informed consent was obtained from all participants.

3D motion analysis (VICONMX, VICON Motion Systems Ltd., Oxford, UK), utilizing seven cameras, was used to measure participants' lumbar and hip angle during lateral trunk bending. Based on a previous protocol[5, 14], seven spherical markers were placed, 14 mm in diameter, on the following anatomical landmarks: right and left posterior superior iliac spine (PSIS), right and left of the T11 spinous process over the paravertebral muscles, and the T10, T12, and S3 spinous processes. Spherical markers for the Plug-in-Gait model[15, 16] in addition to our own marker set were attached. In comparison with the Plug-in-Gait model marker sets[15, 16], our marker sets are able to calculate the detailed lumbar spine angle as four markers were placed on thoracolumbar area.

During lateral trunk bending, the marker trajectories were obtained at 100 Hz using 3D motion analysis with ground reaction forces obtained at 1 kHz using two force plates (AMTI OR6, Advanced Mechanical Technology, Inc., MA, USA). Participants were asked to stand with their feet shoulder-width apart and perform lateral trunk bending by stretching their arm to the lateral malleolus without touching anywhere, four times to the right and left sides. The participants were also allowed to translate their hips to the opposite side of the lateral bending. Lateral trunk bending was performed over 16 s periods demarcated using a metronome (ME-110, Yamaha Corp., Japan); the participants were asked to stand in a neutral position for the first 4 s, bend the trunk laterally to the maximal position for the next 4 s, return to the neutral position for the subsequent 4 s, and stand in neutral position for the final 4 s.

The signals from the marker trajectories and ground reaction forces during trunk motion were filtered with a fourth-order zero-phase Butterworth low-pass filter (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, Vicon Body Builder 3.6.1 (VICON Motion Systems Ltd., Oxford, UK) was used to calculate hip angle, COM for the whole body, waist (lumbar) and hip moment, and lumbar and hip power. The joint moment was considered to be the muscle strength and the positive/negative value of the joint powers were considered to be the concentric/eccentric muscle contraction.

Based on the static position, lumbar spine angle[5, 14] and hip angle[15, 16] were calculated. The code data obtained during trunk bending to the left side were converted to match the code data from trunk bending to the right side. In our analysis, the right lower limb was on the loaded side, which was ipsilateral to the lateral trunk bending, and the left limb was on the unloaded side. Data from four trials were averaged for each participant.

From the data collected during lateral bending, the LHR was calculated as the ratio of the lumbar spine angle to the average of both sides of the hip angle (LHR: Lumbar spine angle/Hip angle[2, 3]). COM and joint moment were normalized by the participants' height and weight, respectively. The bilateral hip moments and powers were averaged. The start of movement was defined as the point when the average of the hip angle of both sides became larger than 1° and the end of movement was when the average was below 1°. The data were separated into two phases according to the hip angle: the descending phase (from the start of movement to when the average of both sides of the hip angle reached their maximum) and the ascending phase (from the point when the average of both sides of the hip angle start decreasing from their maximal value to the end of movement). After separating both phases, the time taken for each phase of the LHR was normalized to 100% and separated into 10% portions for statistical analysis. Accordingly, the COM, lumbar and hip moments, and lumbar and hip powers were divided into the two phases and normalized in the same way.

SPSS ver. 19.0 (International Business Machines Corporation., NY, USA) was used for statistical analysis. One-way repeated measures ANOVA was used to analyze the change in LHR for each 10% portion. Tukey's honest significant difference post hoc test was used to test significant main effects. Curve estimation (linear, quadratic, and cubic functions) was used to describe the LPR. The level of significance was set at $p<0.05$.

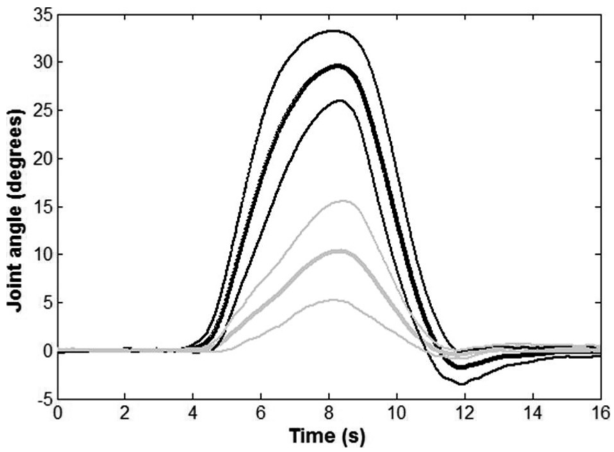

Fig. 1. Lumbar spine angle and hip angle during lateral trunk bending

The thick black line represents the mean lumbar spine angle, and the thin black lines represent the positive and negative standard deviation of the lumbar spine angle. The gray thick line represents the average of the hip angle for both sides, and the gray thin lines represent the positive and negative standard deviation of the hip angle.

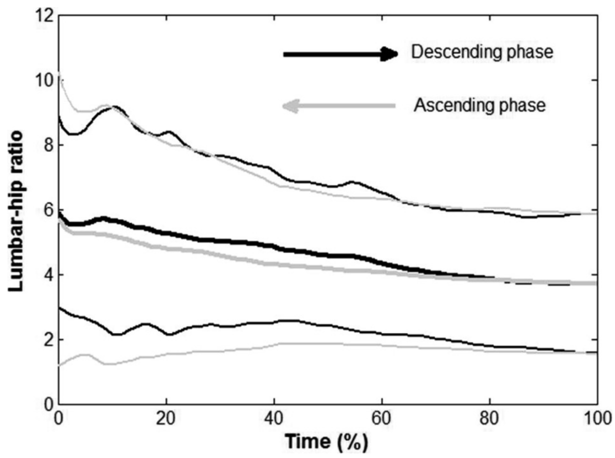

Fig. 2. Lumbar-hip ratio (LHR) during the descending phase and ascending phase

The thick black line represents the mean and the thin black lines represent the positive and negative standard deviations of the LHR during the descending phase. The thick gray line represents the mean and the gray thin lines represent the positive and negative standard deviations of the LHR during the ascending phase.

RESULTS

During lateral bending, the mean maximum angle of loaded-side hip abduction, unloaded-side hip adduction, and averaged bilateral hip motion were 10.6 ± 5.9°, 10.1 ± 5.8°, and 10.3 ± 5.7° respectively. The mean maximum angle of the lumbar spine was 29.5 ± 3.6° (Fig. 1).

In the descending phase, the LHR significantly decreased from 5.9 to 3.6 [$F(10, 70)=3.210$, $p=0.02$], with a mean of 4.5. This indicated lumbar spinal movement was less than hip movement in the late phase. In the ascending phase, LHR significantly increased from 3.6 to 5.6 [$F(10, 70)=3.871$, $p<0.001$], with a mean of 4.2. This indicated a larger lumbar spinal movement compared with hip movement in the late phase (Fig. 2).

The change in LHR was better fit with a cubic function (descending phase: $y=0.001x^3-0.219x^2+4.944x+0.884$, $r^2=0.999$, $p<0.001$, standard error [SE] for estimate=0.2°; ascending phase: $y=-0.012x^3+0.120x^2+2.568x+3.315$, $r^2=1.000$, $p<0.001$, SE for estimate=0.1°) or quadratic function (descending phase: $y=-0.210x^2+4.895x+0.949$, $r^2=0.999$, $p<0.001$, SE for estimate=0.2°; ascending phase: $y=-0.092x^2+3.637x+1.933$, $r^2=0.999$, $p<0.001$, SE for estimate=0.2°) than linear function (descending phase: $y=2.4x+6.7$, $r^2=0.955$, $p<0.001$, SE for estimate=1.5°; ascending phase: $y=2.5x+4.4$, $r^2=0.992$, $p<0.001$, SE for estimate=0.7°) (Fig. 3), where y and x indicate lumbar spine angle and hip angle, respectively. The linear functions showed that when the hip was inclined by 1°, the lumbar spine bent laterally by 2.4°.

The mean maximum moment of the lumbar spine during contralateral bending was 0.75 Nm/kg. The mean maximum moment of loaded-side hip adduction was 0.11 Nm/kg and that of unloaded-side hip abduction was 0.41 Nm/kg. The loaded-side hip adductor muscles and the unloaded-side hip abductor muscles contracted eccentrically during the descending phase. The inferior and ground reaction force of the loaded side was increased when approaching the end of the lateral bending movement. The mean maximum change in the COM was 6.3% ipsilaterally and 3.8% inferiorly. Conversely, during the ascending phase, eccentric and concentric muscle contractions were reversed.

DISCUSSION

The Plug-in-Gait marker set with our own marker set for measuring the lumbar spine angle and hip angle using 3D motion analysis could assess the LHR during lateral trunk bending. The results are consistent with those of previous studies, in particular the study performed by Dvorak et al.[7] who reported a maximum angle of 29°. The maximum angle of the lumbar spine recorded in our study was 29.5°. Furthermore, Wong and Lee[4] reported a maximum hip abductor and adductor angle of 11.9° and 11.5°, which is comparable with our hip angle results.

Participants moved the lumbar spine more than the hip to maintain balance during lateral bending. In the descending phase, they decreased the amount of lumbar spine motion compared with the hip, which decreased LHR. It was also found that the LPR could be better represented by a quadratic or cubic function than a linear function during lateral trunk bending

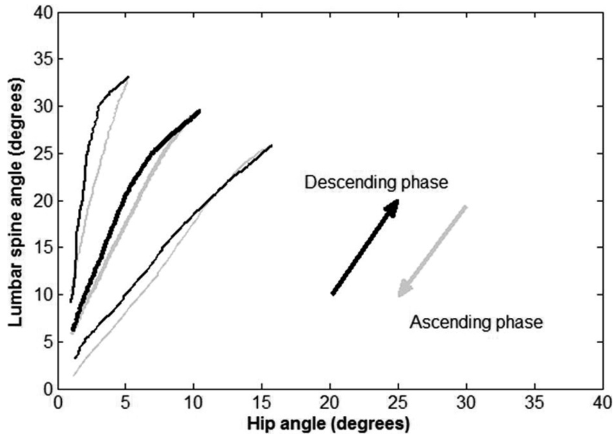

Fig. 3. Lumbopelvic rhythm (LPR) during the descending phase and ascending phase
The thick black line represents the mean and the thin black lines represent the positive and negative standard deviations of the LPR during the descending phase. The thick gray line represents the mean and the thin gray lines represent the positive and negative standard deviations of the LPR during the ascending phase.

for both ascending and descending phases. The coefficient of r^2 for the quadratic and cubic functions was higher than that of the linear function. Furthermore, the SE of the estimate of cubic function or quadratic function was lower than that of linear function. The maximum SE of the estimate was under 1.5°, found in the linear function; however the linear function would also have been reliable. When the angle of lateral trunk bending was increased, the angle of hip movement increased instead of being limited by lateral lumbar bending. This relationship between lumbar and hip movement during lateral trunk bending is indicated by a curved line.

The linear description of the LPR indicates that as the loaded-side hip abducts 1° and unloaded-side hip adducts 1°, the lumbar spine laterally bends 2.4°. Wong and Lee[4)] reported that the LHR was 2.4 and 2.7 at the maximum lateral bending position, with an LHR of 2.5. The muscle strength balance for lateral trunk bending muscles and hip abductor/adductor muscles might cause LHRs over 1.0. The joint moment for lateral trunk bending muscles[17)] were stronger than hip abductor/adductor muscles[18)]. Therefore, in comparison with hip muscles, they mainly contracted contralateral trunk muscles eccentrically to bend their lumbar spine laterally.

Furthermore, in the descending phase, the strategy of the hip on the loaded and unloaded side played an important role for maintaining balance. In the frontal plane, the unloaded-side hip abductors were eccentrically contracted more than the loaded-side hip adductor muscles. The joint moment of the hip abductor muscles was stronger than hip adductor muscles[18)], which could easily control lateral weight shifting. Subjects could control both hips to keep their weight shifted at an intermediate position in the frontal plane without falling to the ground.

In contrast, during the ascending phase, the opposite motion of the descending phase causes the LHR to increase. The contralateral trunk muscles, unloaded-side hip abductor muscles, and loaded side hip adductor muscles were concentrically contracted to reverse the trunk back to the neutral position.

A limitation of this study is that further research using a radiographic technique is needed to validate our marker method for calculating the lumbar angle. Furthermore, a large number of male and female participants with various speeds of motion would have been a significant addition to this study.

The clinical implication of this study is that this method for measuring LPR and LHR would be a useful tool for the assessment of lumbar movement in patients with spinal/hip disorders such as hip-spine syndrome, scoliosis, and balance disorders.

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