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Original Paper

Biomedical Human Kinetics, 15, 131–138, 2023
DOI: 10.2478/bhk-2023-0016

Differences in joint angles during pole vaulting between male pole vaulters with and without chronic low back pain

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Abstract

Study aim: To determine the difference in joint angles of the shoulder, hip, and trunk (angle of the upper torso and lower torso) during vaulting between male pole vaulters with and without chronic low back pain (LBP) and to examine the relationship between the range of motion (ROM) and maximum angle of the same joint during vaulting in all participants.
Material and methods: This cross-sectional study included 17 male vaulters. The participants were divided into two groups (chronic LBP and control) based on their questionnaire results. Four high-speed cameras were used to record at 240 Hz from the touchdown of the last step on the run-up to the pole straight phase. The vaulter cleared the bungee bars that were set at 90% of their personal best record. The ROM of hip flexion and extension, shoulder flexion, and straight leg raise were measured.
Results: There was no difference in the joint angles between the chronic LBP group and control group. In contrast, there was a significantly positive correlation between ROM and the maximum joint angle during hip extension ($p = 0.01$, $r = 0.58$).
Conclusions: Insufficient hip ROM may result in compensatory motion in lumbar extension during pole vaulting.

Key words: Back pain – Lumbago – Track and Field – 3D-DLT

Introduction

Pole vaulters often experience low back pain (LBP). Rebella reported that the lower back is the most common injury location among collegiate pole vaulters [18]. Previous studies have reported a chronic LBP prevalence of 40.0% in male collegiate pole vaulters [7], and the occurrence of LBP was 55.6% in a 1-year observational study of collegiate pole vaulters and decathletes [6]. In addition, the prevalence of lumbar spondylolysis and intervertebral disc degeneration was 28.6% and 38.1%, respectively [8].

In the comprehensive model for injury causation [1], Bahr and Krosshaug proposed that injuries may occur due to the following internal risk factors: basic factors such as age and sex, physical factors such as muscle strength and range of motion (ROM), and technical factors such as sport-specific techniques. Previous studies have examined the physical factors associated with chronic LBP in male collegiate pole vaulters and the occurrence of LBP in collegiate pole vaulters and decathletes [6, 7]. In the reported result, the occurrence of LBP was associated with limited hip flexion and extension ROM, suggesting that compensatory movements of the lumbar region occur when vaulters with limited ROM perform pole vaulting, which induces LBP. Gainor et al. reported an association between pole-vaulting motions and lumbar spondylolysis in three vaulters and pointed out that the maximum angular acceleration of a hyperextending spine occurred during take-off (TO) [11]. In addition, Edouard et al. reported that some biomechanical parameters such as the lower height of the gripping hand from the ground at TO, higher approach speed, contact time on the floor, last stride adjustment, and stride length validity in the approach phase were associated with a higher proportion of all injuries [5].

However, Gainor et al. examined only vaulters with lumbar spondylolysis [11], and the detailed method of video collection is unknown. It is also unclear whether the findings of these previous studies are related to chronic LBP or the occurrence of LBP. Motion factors (such as differences in skill level and vaulting) may cause chronic LBP [1], which has not been previously studied. A previous study reported that the maximum hip flexion angle

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on the TO leg during pole vaulting in the vaulters with lumbar disc degeneration was significantly smaller than that in the vaulters without lumbar disc degeneration [9]. Therefore, if the joint angles of the joints adjacent (such as shoulder or hip) to the lumbar region during pole vaulting are small, there may be increased mobility in the lumbar region. In addition, the relationship between ROM and the maximum joint angle during pole-vaulting is unclear. In related joints, improving the joint ROM may contribute to injury prevention.

Our primary aim was to determine the difference in shoulder, hip, and trunk joint angles during pole vaulting between male pole vaulters with and without chronic LBP. The secondary aim was to examine the relationship between ROM and the maximum angle of the same joint during vaulting. We hypothesized that vaulters with chronic LBP would have smaller shoulder or hip joint angles during pole vaulting.

Material and methods

Population

This was a cross-sectional study conducted in the Tokai area of Japan and included 17 male pole vaulters (mean ± standard deviation; height, 172.5 ± 4.5 cm; body mass, 66.8 ± 6.7 kg; age, 22.6 ± 3.5 years; personal best record of pole vault, 5.0 ± 0.3 m; period of pole vault, 10.0 ± 2.6 years). The inclusion criteria were pole vaulters in the Tokai area ≥ 18 years of age as of March 2019. Although 30 athletes met the inclusion criteria, consent for this study could not be obtained from 13 athletes; thus, 17 athletes, the majority of whom were collegiate athletes, provided written informed consent and were finally included in the study. The evaluation was performed independently of whether the athletes had LBP. The study protocol conforms to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a prior approval by the Chukyo University Research Ethics Committee (No. 2018-064).

Questionnaire and ROM

A procedure employed in previous studies [6, 7] was used to investigate information regarding vaulter demographics using a questionnaire and to measure ROM. A self-report questionnaire was used to investigate information regarding vaulter demographics, such as age, height, body mass, personal best record, and period of competition in the pole vault. The participants were divided into two groups (chronic LBP and control) based on their questionnaire results. Those who answered "Yes" to the question, "Do you often experience LBP during pole vaulting?" were assigned to the chronic LBP group. The TO leg was also investigated using the same questionnaire and was defined as the leg used during vaulting. The opposite leg was defined as the lead leg.

This study measured the active and/or passive ROM and muscle flexibility of the participants in the supine position on a bed. All measurements were recorded using a camera (EX-F1, CASIO, Tokyo, Japan) and analyzed using an image analysis software (NIH ImageJ ver. 14.4). This study subtracted active ROM from passive ROM and indicated it as Δ, which represented the ability to actively control movements, excluding the limits of an individual's muscles and joints. The following measurements were performed on both sides:

1) Passive shoulder flexion: The angle between a line connecting the two landmarks on the humerus and a line parallel to the trunk.
2) Passive hip flexion and extension: The angle between the line connecting the greater trochanter and the lateral epicondyle of the femur and a line parallel to the trunk.
3) Active/passive straight leg raise (SLR): The angle between a line connecting the greater trochanter to the lateral malleolus and a line parallel to the trunk. The ankle joint was in a neutral position during the measurement.

Biomechanical analysis

The video for motion analysis was recorded from four views with the planting box at the center (Fig. 1), at 240 Hz with four high-speed cameras (GC-LJ20B, JVC, Kanagawa, Japan). The calibration area was set based on the left edge of 0 m in the direction of run-up on the runway, with a distance of 5 m on the runway side and 2.5 m on the mat side; a width of 1.25 m on the left side and 2.5 m on the right side of the runway; and a height of 5 m. Calibration poles of 5 m in height (0.5 m between marks) were set up at 10 points in the range and projected on video. For the experimental trials, the vaulter performed on bungee bars that were set at 90% of their personal best record until the vaulter was able to jump over the bar three times, and those three trials were used for the analytical trials. In this study, a bungee bar was used to ensure safety and reduce the burden on the participant [9]. The mean of the three analyzed trials was used for statistical analysis. The vaulter selected the poles and steps for the aforementioned trials.

The video analysis was set from the moment of touchdown (TD) of the last step on the run-up to the moment the pole was straight (PS) (Fig. 2) [10]. The event during pole vaulting was recorded at the TD, TO, maximum pole bending (MPB), and PS. The digitization of body marks was performed manually at 240 Hz using the motion analysis system (Frame-DIAS V, DKH Inc., Tokyo, Japan) for both lower extremities, the knee joint and greater trochanter; for both upper extremities, the shoulder joint and

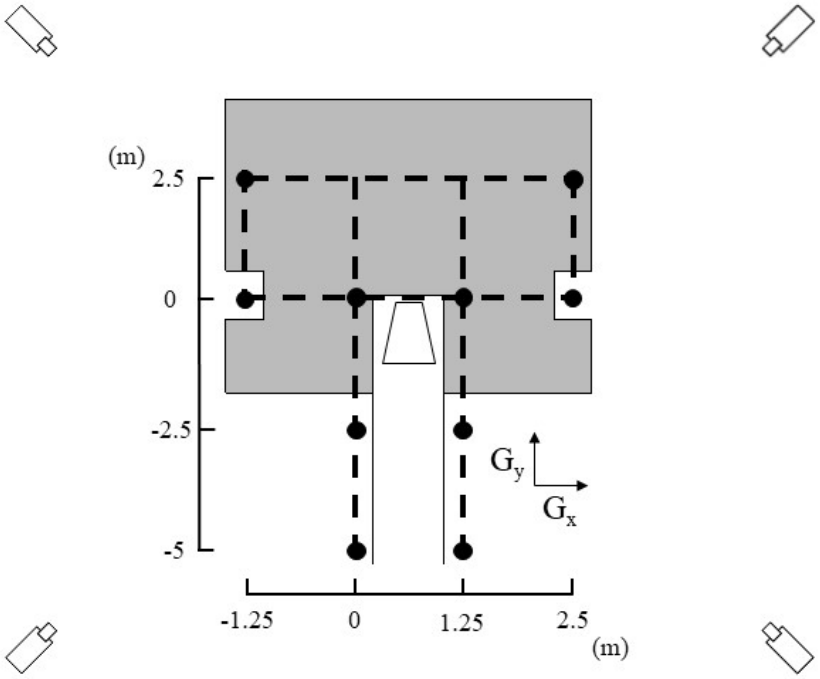


Figure 1. Experimental setup and the definition of the global coordinate system

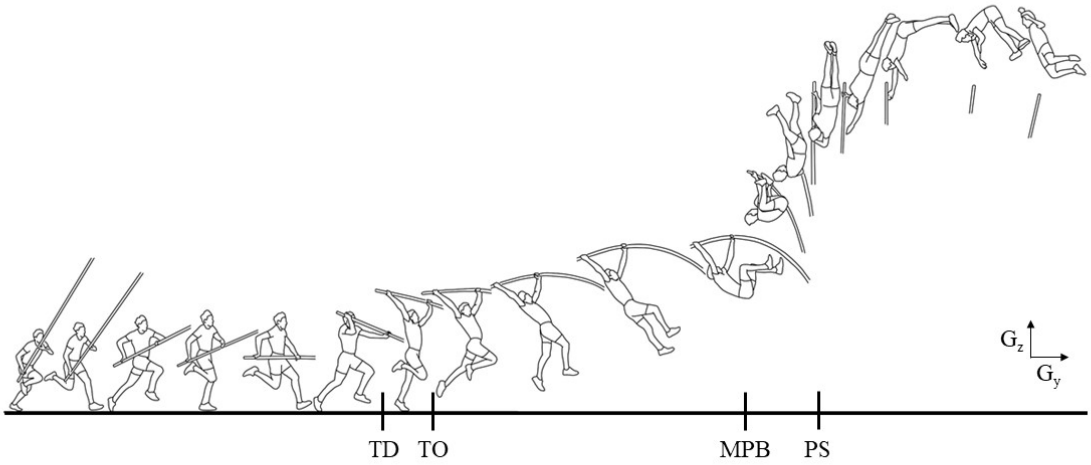


Figure 2. Pole vault model and event definition. Touchdown (TD), take-off (TO), maximum pole bending (MPB), and pole straight (PS)

the 12th rib; and for the elbow and hand of the lead leg side. Taping as markers, were affixed to the elbow, 12th rib, greater trochanter, and knee on both sides. The global coordination system was constructed using G_y in the horizontal direction of run-up, G_z in the vertical direction, and G_x as the cross product of G_y and G_z. The event at MPB was defined as the moment when the distance between the hand on the lead leg side and the center of the planting box was at a minimum [12, 20]. This event definition was used as the method in previous studies [12, 20], and MPB was calculated using pole length and string length. Therefore, it was the shortest distance between the box and grip in this study. The maximum standard errors of the control points in each axis were 0.023 m in the x, 0.020 m in the y, and 0.011 m in the z axes. Analysis point smoothing was performed by determining the optimal cutoff frequency (13.2–21.0 Hz) and using a low-pass Butterworth digital filter [22]. The data for each participant were normalized by time, with 0% for TD and 100% for PS. The joint angles during vaulting were calculated from digitized data using the three-dimensional direct linear transform (3D-DLT) algorithm. In this study, only joint angles within the Y-Z plane were calculated for the joints (shoulder, hip, and trunk) that may be associated with chronic LBP. The detailed method for calculating the joint angles is described below.

(1) Shoulder joint angle (lead leg side)

For the upper trunk segment moving coordinate system, x_{ut} was defined as the unit vector from the lower left rib end to the lower right rib end, and z_{ut} was defined as the unit vector from the midpoint of the lower rib end to the midpoint of the shoulder joint. Subsequently, y_{ut} was determined by extrapolating x_{ut} and z_{ut} and $x_{ut'}$ by extrapolating y_{ut} and z_{ut}. The shoulder angle was defined as the angle formed between the projected vector z_{ua} from the shoulder joint to the elbow joint and $-z_{ut}$ within the $y_{ut}z_{ut}$ plane.

(2) Hip joint angle (both legs)

For the moving coordinate system of the lower torso segment, the unit vector from the left to the right greater trochanter was defined as x_{lt}, and the unit vector from the midpoint of the greater trochanter to the midpoint of the lower end of the ribs was defined as z_{lt}. Then, y_{lt} was determined by extrapolating x_{lt} and z_{lt} and $x_{lt'}$ by extrapolating y_{lt} and z_{lt}. The hip angle was defined as the angle formed between z_{th} from the greater trochanter to the knee joint and $-z_{lt}$ within the $y_{lt}z_{lt}$ plane. From the upright position, flexion was considered positive and extension, negative.

(3) Trunk angle

Projection of the unit vector z_{lt} from the midpoint of the tensor to the midpoint of the inferior end of the ribs in the plane was defined as $y_{ut}z_{ut}$ in the moving coordinate system of the upper torso segment. The trunk angle was defined as the angle between the projected vector z_{lt} and $-z_{ut}$. From the upright position, flexion was considered positive and extension, negative.

Statistical analysis

All data analyses were performed using SPSS version 23 (IBM Corp., Armonk, NY, USA). The normality of all data was analyzed using the Shapiro-Wilk test. Differences in data with normal and skewed distribution between the chronic LBP group and control group were analyzed using an unpaired t-test and the Mann-Whitney U test, respectively. Results were expressed as mean ± standard deviation (95% confidence interval) with an effect size. Normalized data were compared between the groups every 1% normalization time using the Mann-Whitney U test. The Hedge's g or r value was calculated as effect sizes [3]. The Hedge's g as an effect size was interpreted as follows: <0, adverse effect; 0–0.20, no effect; 0.20–0.50, small effect; 0.50–0.80, intermediate effect; and ≥0.80, large effect. The r value as an effect size was interpreted as follows: 0.10–0.30, small effect; 0.30–0.50, intermediate effect; and ≥0.50, large effect [16]. Pearson and Spearman's correlations were used to examine the relationships between ROM and the maximum joint angle during pole vaulting. The coefficient of variation of the maximum joint angles in the three trials performed by each athlete was calculated. Results were considered statistically significant at the 5% level ($p < 0.05$).

Results

The questionnaire results showed that nine vaulters had chronic LBP and eight vaulters did not. There was no statistically significant difference in the population statistics and ROM between the chronic LBP and control groups (Tables 1 and 2).

The difference in joint angle between groups

The average number of trials over the bungee bar, which was set at 90% of the personal best record, was four trials (min-max: 3–7). The motion time from TD to PS was 1.17 ± 0.08 s, and the motion times for each phase were 0.12 ± 0.01 s for TD-TO, 0.54 ± 0.04 s for TO-MPB, and 0.51 ± 0.06 s for MPB-PS. The mean values of each event

Table 1. Comparison of population statistics between the chronic LBP group and control group

Variables	Chronic LBP (n = 9)		Control (n = 8)		*p*-value	Effect size
	Mean ± SD	95% CI	Mean ± SD	95% CI		
Age [years] [a]	22.4 ± 3.2	19.9–24.9	22.8 ± 3.9	19.5–26.1	0.96	0.01
Height [cm]	173.6 ± 3.8	170.7–176.5	171.5 ± 5.0	167.3–175.7	0.36	0.44
Body mass [kg]	64.6 ± 6.2	59.8–69.4	68.8 ± 6.9	63.0–74.6	0.21	0.61
Personal record [m]	5.1 ± 0.3	4.9–5.3	4.9 ± 0.3	4.6–5.2	0.37	0.43
Period of pole vault [years]	9.5 ± 2.1	7.9–11.1	10.4 ± 3.1	7.8–13.0	0.50	0.32

LBP = low back pain; SD = standard deviation; CI = confidence interval; [a] The Mann-Whitney U test and r value as an effect size were used for analysis, with normality tested based on the Shapiro-Wilk test. An unpaired t-test and Hedges' g as an effect size were used to analyze the other variables.

Table 2. Comparison of ROM between the chronic LBP group and control group

Range of motion (deg)	Chronic LBP (n = 9)		Control (n = 8)		*p*-value	Effect size
	Mean ± SD	95% CI	Mean ± SD	95% CI		
Takeoff leg side						
Passive hip flexion	115.8 ± 8.0	109.7–121.9	117.3 ± 7.1	111.4–123.2	0.69	0.19
Passive hip extension	18.2 ± 5.5	14.0–22.4	14.2 ± 5.0	10.0–18.4	0.14	0.73
Passive shoulder flexion	162.7 ± 6.2	157.9–167.5	160.4 ± 9.4	152.5–168.3	0.57	0.27
Passive SLR	75.0 ± 6.2	70.3–79.8	75.5 ± 8.5	68.4–82.6	0.90	0.06
Active SLR	71.0 ± 9.0	64.1–77.9	70.7 ± 8.2	63.9–77.5	0.94	0.03
Δ SLR	4.0 ± 6.6	0.0–9.1	4.8 ± 4.3	1.2–8.4	0.78	0.13
Lead leg side						
Passive hip flexion	116.8 ± 7.4	111.1–122.5	121.3 ± 5.4	116.8–125.8	0.18	0.66
Passive hip extension	17.1 ± 6.2	12.3–21.9	14.5 ± 3.3	11.7–17.3	0.30	0.49
Passive shoulder flexion	165.4 ± 6.1	160.7–170.1	163.4 ± 7.0	157.5–169.3	0.52	0.30
Passive SLR	77.4 ± 5.0	73.5–81.2	80.6 ± 3.7	77.5–83.7	0.15	0.69
Active SLR	72.3 ± 9.0	65.4–79.2	76.1 ± 5.4	71.6–80.7	0.31	0.49
Δ SLR	5.1 ± 6.3	0.3–10.0	4.5 ± 4.7	0.6–8.4	0.82	0.11

LBP = low back pain; SD = standard deviation; CI = confidence interval; SLR = straight leg raise; ROM = range of motion; An unpaired t-test and Hedge's g as an effect size were used to analyze all variables with normality tested based on the Shapiro-Wilk test.

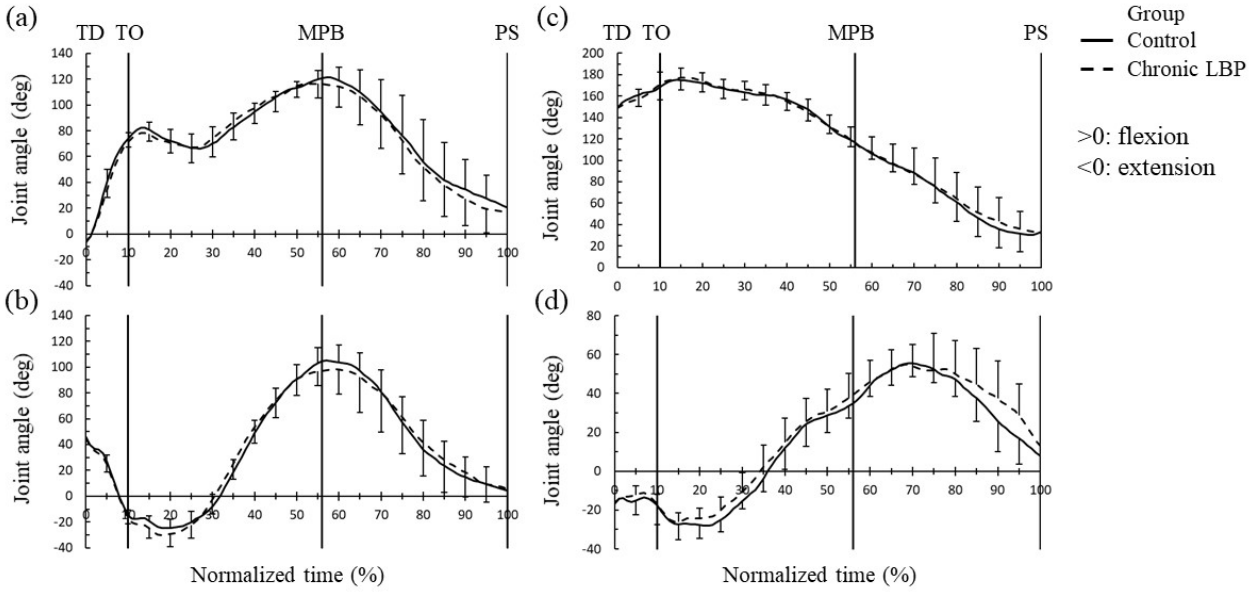


Figure 3. Average patterns of joint angle displacement. Hip joint angle on the (a) lead leg and (b) take-off leg, (c) shoulder joint angle on the lead leg side, and (d) trunk angle

at the normalized time for both groups and the range (min-max) were 0% for TD, 10% for TO (8–13% for the chronic LBP group and 10–13% for the control group), 56% for MPB (54–60% for the chronic LBP group and 50–65% for the control group), and 100% for PS. The mean values of both groups regarding the time-series change for each joint are shown in Fig. 3. There was no statistically significant difference in all joint angles between the groups.

Table 3. Correlation between range of motion and maximum joint angle during pole vaulting

Joint	Maximum joint angle [deg]		Coefficient of variation		Correlation with ROM of the same joint		
	Mean ± SD	95%CI	Mean ± SD	95%CI	r	95%CI	*p*-value
Takeoff leg side							
Hip flexion	110.0 ± 10.3	104.7–115.3	0.05 ± 0.02	0.04–0.06	–0.23	–0.64–0.28	0.38
Hip extension	30.9 ± 8.0	26.8–35.0	0.13 ± 0.07	0.09–0.17	0.58	0.14–0.83	0.01*
Lead leg side							
Hip flexion	124.8 ± 9.6	119.9–129.7	0.05 ± 0.02	0.04–0.06	–0.13	–0.58–0.37	0.62
Hip extension	7.8 ± 5.5	5.0–10.6	0.71 ± 0.87	0.26–1.16	0.11	–0.39–0.56	0.67
Shoulder flexion	180.3 ± 8.8	175.8–184.8	0.02 ± 0.02	0.01–0.03	0.17	–0.34–0.60	0.52

SD = standard deviation; CI = confidence interval; SLR = straight leg raise; ROM = range of motion; *Significant difference at $p < 0.05$; An unpaired t-test and Hedge's g as an effect size were used to analyze all variables with normality tested based on the Shapiro-Wilk test.

Correlation between ROM and the maximum joint angle

During hip extension of the TO leg, there was a significantly positive correlation between ROM and the maximum joint angle during pole vaulting ($p = 0.01$, $r = 0.58$, Table 3). No statistically significant correlations were found for other joints.

Discussion

This study aimed to determine the difference in joint angles of the shoulder, hip, and trunk during pole vaulting between male pole vaulters with and without chronic LBP, and to examine the relationship between ROM and maximum angle of the same joint during vaulting. No statistically significant differences were observed in shoulder, hip, and trunk joint angles from TD to PS during pole vaulting between male pole vaulters with chronic LBP and male pole vaulters without chronic LBP. Meanwhile, during hip extension of the TO leg, there was a significantly positive correlation between ROM and the maximum joint angle during pole vaulting. Our results contradict our hypothesis that vaulters with chronic LBP would have smaller shoulder and hip angles during pole-vaulting as no statistically significant differences were observed between the groups.

The prevalence of chronic LBP was 52.9% in this study. Many previous studies have defined chronic LBP as LBP that persists for over 3 months [4, 15, 17]. However, LBP is often associated with specific athletic movements, and if the frequency of specific exercises that cause LBP is low, it will not be identified as chronic LBP. Therefore, this study used a questionnaire to investigate chronic LBP based on the participants' responses to how often they experienced LBP during pole-vaulting, and participants responding with a "Yes" to the question, "Do you often experience LBP during pole vaulting?" were classified under the chronic LBP group. Clarsen et al. [2] reported that a prospective injury survey using questionnaires could provide a more accurate picture of injuries in common chronic disorders with persistent pain that do not lead to competitive exclusion. The chronic LBP definition in this study was not influenced by the frequency of performing specific movements during which the pain appeared, which is probably a more accurate determination of chronic LBP.

According to the comprehensive model for injury causation proposed by Bahr and Krosshaug [1], the origin of injury development may be from the internal risk factor that the athlete possesses. The identified internal risk factors include basic factors such as age and sex, physical factors such as muscle strength and ROM, and technical factors such as sport-specific techniques. Previous studies [6, 7] have reported that the occurrence of LBP was associated with limited hip flexion and extension ROM, suggesting that compensatory movements of the lumbar region occur when vaulters with limited ROM perform pole-vaulting, which induces LBP. By confirming that there was no statistically significant difference in population statistics and ROM among our study participants, it was considered that this study could compare the technical factors between the groups. Therefore, it was suggested that there was weak evidence regarding the association between chronic LBP and the shoulder, hip, and trunk joint angles during pole vaulting. There were no statistically significant differences in physical and technical factors between the groups in this study, suggesting that chronic LBP may be caused by other factors that were not measured. Moreover, the vaulters in this study were a moderate-level group who had progressed to the collegiate level or above, thus, eliminating athletes with obvious motion

differences suggests that there was no significant difference in the pole-vaulting motions between groups.

In hip extension, there was a significantly positive correlation between ROM and the maximum joint angle during pole vaulting. In a previous study, only participants without chronic LBP were included in the analysis, and the occurrence of LBP was associated with a limited ROM during hip extension [6]. Kitamura et al. reported that swimmers in the LBP group had a smaller hip extension ROM than that those in the control group [14]. Gainor et al. reported an association between pole-vaulting motions and lumbar spondylolysis [11], and highlighted that the maximum angular acceleration of the hyperextending spine occurred during TO. This study's results and those of the previous studies suggest that low hip extension ROM may cause compensatory movements in the lumbar spine and may be associated with the occurrence of LBP and lumbar spondylolysis. Spondylolysis may be a stress fracture of the pars interarticularis, which frequently occurs in adolescent athletes [13, 19, 21]. There is a general agreement that sports movements that require lumbar hyperextension and rotation constitute a risk for the development of spondylolysis. Therefore, adolescent athletes in particular may need to have a large hip extension ROM to prevent lumbar spondylolysis. Additionally, stress on the lumbar spine may increase by repetitive vaulting involving maximum hip extension, which stretches and damages the psoas muscle that connects the lumbar vertebrae to the femur and acts on hip flexion. However, the movement of the joints within the lower trunk segment is unknown in this study. Thus, it is necessary to clarify the detailed behavior of the lumbar spine in future studies. In addition, the results of this study showed that the mean ROM for hip extension was higher in vaulters with chronic LBP than in vaulters without chronic LBP (not significant, $p=0.14$), with an intermediate effect (Hedge's $g=0.73$). Although this was a cross-sectional study, and cause–effect relationship between hip extension ROM and the occurrence of chronic LBP is unclear, it is possible that chronic LBP has distinct features from LBP and lumbar spondylolysis.

Limitations

This study has several limitations. First, demonstrating a cause-effect relationship between ROM and the maximum joint angle on hip extension during pole vaulting in a cross-sectional study was impossible. Second, this study had a limited sample size, and only male vaulters were assessed. This study could not recruit female collegiate athletes and, thus, excluded them to avoid the effects of sex differences. The training condition, training content, performance level of pole vaulting, and sex may have influenced chronic LBP. A sample size of each group (chronic LBP: n=9, control: n=8) gave post hoc power of 0% to 39% to detect differences using a two-group t test with a two-sided significance level of $p<0.05$ for differences between the chronic LBP group and control group. Third, this study defined chronic LBP using a questionnaire similar to those used in previous studies. There is no common definition of chronic LBP, and it is necessary to propose a common definition in the future. Nonetheless, it is worth noting that this is the first study to examine the relationship between chronic LBP and joint angles during pole vaulting. In the future, it will be necessary to examine the movement-related factors associated with the occurrence of LBP through prospective studies, to focus on the kinetics of the factors associated with chronic LBP, and to examine the detailed behavior of the lumbar spine during pole vaulting.

In conclusion, although there were no significant differences in technical factors between vaulters with chronic LBP and vaulters without chronic LBP, there was a significant correlation between ROM and maximum joint angle in hip extension of all participants. Therefore, insufficient hip ROM may result in compensatory motion in lumbar extension during pole vaulting. Pole vaulters need to achieve sufficient hip ROM to prevent extension-type LBP and lumbar spondylolysis. Self-massaging of the front of the thighs and pelvis using a form roller or massage ball may help prevent lumbar injuries. Moreover, coaches should ensure that pole vaulters are not hyperextending their lower back during vaulting.

Conflict of interest: Authors state no conflict of interest.

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Received 15.11.2022
Accepted 10.04.2023

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Acknowledgements

The authors appreciate the teachers and assistants of the Graduate School of Chukyo University.