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ORIGINAL RESEARCH

Effects of lower-limb joint mobility and core muscle activation on dynamic lumbar kyphosis during deep squats

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Abstract

Background: Deep squats improves core stability and lower-limb strength. However, dynamic lumbar kyphosis during this movement may increase spinal injury risk. We quantified the dynamic lumbar kyphosis angle during deep squats and examined its association with lower-limb joint angles and muscle activation in the rectus abdominis, external oblique, erector spinae, latissimus dorsi, rectus femoris, gluteus maximus and biceps femoris. Our main aim was to identify strategies for mitigating lumbar kyphosis. **Methods**: Thirty adult men proficient in resistance training participated in the study. Reflective markers were affixed to joints, and surface electromyography (sEMG) electrodes were placed on muscles involved in lumbar flexion and extension. Participants performed deep squats at 70% of their one-repetition maximum, with motion data captured using eight infrared cameras (sampling rate: 250 Hz). Muscle activity was recorded via a wireless sEMG system (sampling rate: 2000 Hz). Peak joint angles and maximum lumbar flexion were analyzed using correlation and stepwise multiple linear regression to identify factors contributing to dynamic lumbar kyphosis ($\alpha = 0.05$). **Results**: Significant positive correlations were observed between maximum hip flexion angle ($r = 0.590$, $p = 0.001$), erector spinae activity ($r = 0.403$, $p = 0.027$), and maximum lumbar flexion angle. Multiple regression analysis identified a model including hip flexion and erector spinae activity ($r = 0.682$, adj. $R^2 = 0.426$, $p < 0.001$), with a hip joint peak flexion angle (HJ_PFA) ($t = 3.910$, $\beta = 0.553$, $p = 0.001$) as the strongest predictor of lumbar flexion angle, followed by erector spinae muscle activity (ES_MA) ($t = 2.436$, $\beta = 0.345$, $p = 0.022$). **Conclusions**: Enhancing hip mobility and erector spinae strengthening prevent dynamic lumbar kyphosis during deep squats. Training programs should incorporate hip mobility exercises, stretching and range of motion routines with resistance exercises targeting the erector spinae.

Keywords

Deep squat; Dynamic lumbar kyphosis; Butt wink; Lumbar injury; Electromyography

1. Introduction

The squat is a fundamental human movement frequently performed in daily life, such as during sit-to-stand transitions, and is widely utilized in sports and strength training to enhance core stability and lower-limb function [1–3]. It is a closed kinetic chain, multi-joint exercise executed with both feet in contact with the ground, necessitating coordinated flexion and extension of the lower-limb joints [4]. The movement's demands on joint stability, mobility, and muscular strength renders it an essential component of performance enhancement, injury prevention and rehabilitation programs.

Squats are typically categorized as partial, half or deep, based on squat depth. Specifically, the deep squat involves a full range of motion of the lower-limb joints to maximize muscle activation and promote strength and hypertrophy in the major muscles of the lower extremities [4–7]. Safe execution requires adequate ankle and hip mobility as well as sufficient core and lower-limb strength to support the load. Deficiencies in these areas can lead to compensatory movement patterns, increasing the risk of musculoskeletal injury, particularly in the lumbar spine and lower extremities [8–10]. To minimize this risk, it is recommended to maintain stability through the feet and knees, ensure sufficient mobility in the ankles and hips, and preserve a neutral or slightly lordotic lumbar spine throughout the movement [8].

The lumbar spine serves a central function during deep squats by linking the trunk and lower limbs, transmitting forces efficiently to the primary movers, and distributing loads across the kinetic chain [11–13]. Preserving neutral lumbar alignment and proper movement patterns is essential to minimize mechanical stress and reduce the risk of injuries such as disc herniation or low back pain [14]. In general, the recommendation is to maintain neutral lumbar alignment and minimize kyphotic movement during deep squats. Despite these recommendations, many individuals exhibit excessive lumbar flexion at the bottom of a deep squat, a phenomenon referred to as dynamic lumbar kyphosis.

Dynamic lumbar kyphosis refers to the involuntary rounding of the lumbar spine from a neutral position at the bottom of a deep squat [15, 16]. This movement, commonly known as the "butt wink" due to its visual appearance, results from a loss of lumbar control during the squat and has been shown to increase both shear and compressive forces on the spine, potentially raising the risk of injury [11, 15, 17, 18]. Although dynamic lumbar kyphosis is considered a movement to be avoided during deep squats, scientific evidence identifying its precise causes to establish effective corrective strategies remains lacking.

To prevent dynamic lumbar kyphosis during deep squats, it is essential to identify its biomechanical causes and establish intervention strategies based on scientific analysis. Proper coordination and control between the agonists and antagonists responsible for lumbar flexion and extension play a pivotal role [12, 19–21]. Therefore, assessing muscle activation in these groups is necessary for understanding its underlying mechanisms. Moreover, because the deep squat is a closed kinetic chain, multi-joint movement, inadequate mobility in the lower extremity joints can induce compensatory movement patterns, which may contribute to dynamic lumbar kyphosis [5, 22, 23].

In this study, we aimed to identify the biomechanical causes of dynamic lumbar kyphosis that occur during deep squats. Lumbar flexion angles, joint range of motion (ROM) in the lower extremities, and activities of major muscle groups were measured using three-dimensional motion capture and surface electromyography. The significant predictors of dynamic lumbar kyphosis were then identified using stepwise multiple regression analysis. Ultimately, we aimed to provide evidence-based insight for preventing and correcting this movement pattern during deep squats.

2. Materials and methods

2.1 Participants

The sample size for a power analysis was determined using the G*Power 3.1 software (University of Düsseldorf, Düsseldorf, NRW, Germany) (effect size f^2: 0.35, alpha level: 0.05, and power: 0.8); the minimum sample size was calculated to be 28 cases [24, 25]. Thus, 30 adult male participants were recruited (Table 1). The inclusion criteria were: no history of musculoskeletal injuries or postural imbalances involving the lower limbs or lumbar spine within the past year, and the right leg as the dominant leg, proficiency in resistance training, as evidenced by engaging in moderate-to-high intensity resistance training at least three times per week for over one year, a one-repetition maximum (1RM) for a deep squat of ≥100 kg, and visibly demonstrable dynamic lumbar kyphosis during deep squat performance. The participants were recruited over a three-week period from 01 June to 21 June 2022. The study intervention and data collection were subsequently conducted between 27 June and 30 September 2022. All study procedures were approved by the Institutional Review Board of Konkuk University (IRB No. 7001355-202204-HR-543).

2.2 Procedures

This study investigated the presence and contributing factors of dynamic lumbar kyphosis during deep squats. To minimize the risk of participant bias or intentional movement modification, the detailed objectives and focus of the study were not disclosed to participants. A general overview of the procedures and safety considerations was provided prior to testing.

One-week preceding data collection, each participant underwent a 1RM test for the deep squat, conducted according to the guidelines established by the National Strength and Conditioning Association [26]. The results of the 1RM test were used to determine the appropriate load intensity for the deep squat trials in the main experiment.

On the testing day, participants completed approximately 10 min of a brief warm-up routine to minimize musculoskeletal injury risk before beginning the experimental protocol. Before placement of the surface electromyography (sEMG) electrodes, the designated skin areas were shaved and cleansed with alcohol swabs. Seven channels of sEMG electrodes were applied to major muscle groups involved in lumbar flexion and extension. To normalize raw sEMG signals obtained during the deep squat trials, the maximal voluntary isometric contraction (MVIC) of each muscle was recorded for approximately 5 s. Following MVIC measurement, participants were provided at least 30 min of rest to mitigate fatigue before proceeding with the motion capture phase. Using the Plug-in Gait model provided by Vicon Motion Systems Ltd., Oxford, UK [27], 51 spherical reflective markers (diameter: 15 mm) were attached to anatomical landmarks across the participants' limbs and torso. A global coordinate system was established within the lab space using Vicon's Active Wand for calibration, with the anterior-posterior axis defined as the Y-axis, the mediolateral axis as the X-axis, and the vertical axis as the Z-axis. Motion data were captured using eight infrared cameras (MX-T10S, Vicon Inc., Oxford, UK) at a sampling rate of 250 Hz. Following the recording of a static trial in the anatomical position, dynamic trials were conducted wherein participants executed

TABLE 1. Physical characteristics of study participants.

Variables (unit)	Participants (n = 30)			
	Age (yr)	Height (cm)	Weight (kg)	SQ 1RM weight (kg)
Mean ± SD	23.4 ± 3.5	175.3 ± 4.3	75.8 ± 6.5	115.3 ± 19.5

Abbreviations: SQ: squat; 1RM: 1 repetition maximum; SD: Standard deviation.

three repetitions of deep squats under loaded conditions.

2.3 Deep squat exercise

Participants performed the barbell back squat. To initiate the movement, the feet were positioned at approximately 100%–120% of pelvic width with 15°–30° of external rotation, adhering to the standard deep squat technique. The barbell was positioned across the upper back, centered between the spinous process of the seventh cervical vertebra (C7) and the scapula. Load intensity was set at 70% of each participant's 1RM, consistent with hypertrophy-focused resistance training guidelines [26].

To ensure proper depth, participants flexed their knees until the posterior thighs contacted the calves, with knee flexion exceeding 120° [28]. Each participant completed three repetitions of the deep squat. Prior to testing, all participants practiced the movement to ensure consistent execution. During data collection, movement cadence was standardized using a metronome set at 120 bpm, with approximately 2 seconds for the descent phase and 1.5 seconds for the ascent phase.

2.4 Wireless sEMG system

Muscle activities during lumbar flexion and extension were measured using a seven-channel wireless sEMG system (Trigno Sensor System, Delsys Inc., Natick, MA, USA), using silver/silver chloride (Ag/AgCl) electrodes (37 mm × 26 mm × 15 mm; interelectrode distance: 10 mm) at a sampling rate of 2000 Hz. Given the complexity of lumbar motion, which involves multiple muscle groups including deep spinal stabilizers not easily accessible via surface EMG, this study focused on major superficial muscles involved in lumbar flexion and extension that are suitable for surface recording.

Based on surface EMG for non-invasive assessment of muscle guidelines and previous literature, electrodes were attached to the following muscles: rectus abdominis (RA), external oblique (EO), erector spinae (ES), latissimus dorsi (LAT), rectus femoris (RF), gluteus maximus (GM), and biceps femoris long head (BFL) [12, 29–34]. All participants exhibited no left-right asymmetry and identified the right leg as dominant; therefore, surface electrodes were placed on the right side for consistency.

2.5 Biomechanical lumbar model based on reflective markers

Lumbar kinematic data during deep squats were calculated using a biomechanical spine model known as the S-Model (University of Miami S Model, Vicon). The S-Model is an extension of Vicon's Plug-in-Gait model, specifically designed to estimate spinal segment positions using reflective marker data. This model facilitates the calculation of lumbar joint kinematics by incorporating the mass and inertial properties of each segment [35]. The validity of the S-Model has been demonstrated previously, with Eltoukhy *et al.* [36] confirming its accuracy through comparisons with direct measurements of lumbar segment positions and ROM. In the present study, the S-Model was applied to both static and dynamic trials for each participant to estimate seven virtual markers corresponding to the L4 and L5 vertebral segments. The coordinate data for the virtual markers of L4 and L5 were exported as C3D files and imported into Visual3D software (v6, C-Motion, Inc., Germantown, MD, USA). Local coordinate systems were established for each of the L4 and L5 segments (Fig. 1), and the relative angles between the two segments were calculated to quantify lumbar joint motion.

2.6 Data processing

Kinematic and electromyographic data collected during the deep squat trials were synchronized using Giganet (Data acquisition device, Vicon Motion Systems Ltd., Oxford, UK), which linked eight infrared motion capture cameras with a wireless sEMG system. Subsequently, raw data were obtained and C3D files were generated using Nexus software (version 2.14; Vicon Motion Systems Ltd., Oxford, UK).

Static and dynamic trial C3D files for each participant were imported into Visual3D software (C-Motion, Inc., Germantown, MD, USA) for analysis. To eliminate noise artifacts from the motion capture data, a second-order low-pass Butterworth filter with a cutoff frequency of 6 Hz was applied to the reflective marker trajectories. sEMG signals were filtered using a band-pass filter set between 50 and 450 Hz, followed by full-wave rectification. The filtered sEMG data were then smoothed using a 100 ms moving average and root mean square calculations. All muscle activation data were normalized to each participant's MVIC values.

To analyze the biomechanical contributors to dynamic lumbar kyphosis during deep squats, five key events and four analytical phases were defined. The ready event marked the starting posture; start of lumbar kyphosis indicated the onset of lumbar flexion during the descending phase; maximal lumbar kyphosis represented the point of maximal lumbar flexion; end of lumbar kyphosis marked the point at which lumbar extension resumed during the ascending phase; and the finish event indicated the end of the squat movement. Joint angle variables for the lower extremities were analyzed during the descending phase, while muscle activities were analyzed during the lumbar flexion phase (Fig. 2).

During deep squats, joint angles of the lower extremities and lumbar spine were calculated using a local coordinate system defined with the mediolateral axis as the X-axis, the anteroposterior axis as the Y-axis, and the vertical axis as the Z-axis. The peak relative angles of the ankle, knee and hip joints in each direction as well as the maximum flexion angle between L4 and L5 were computed using the Cardan orientation method. The joint angles for the lower extremity and lumbar spine in each direction were defined based on their respective local coordinate systems (Table 2).

All joint angles were calculated during the descending phase, and muscle activities were extracted during the lumbar flexion phase, which corresponded to the period of lumbar flexion within the deep squat.

2.7 Statistical analysis

The determinants of dynamic lumbar kyphosis during deep squats were investigated using Pearson's correlation analysis to examine the relationships between maximum joint angles of

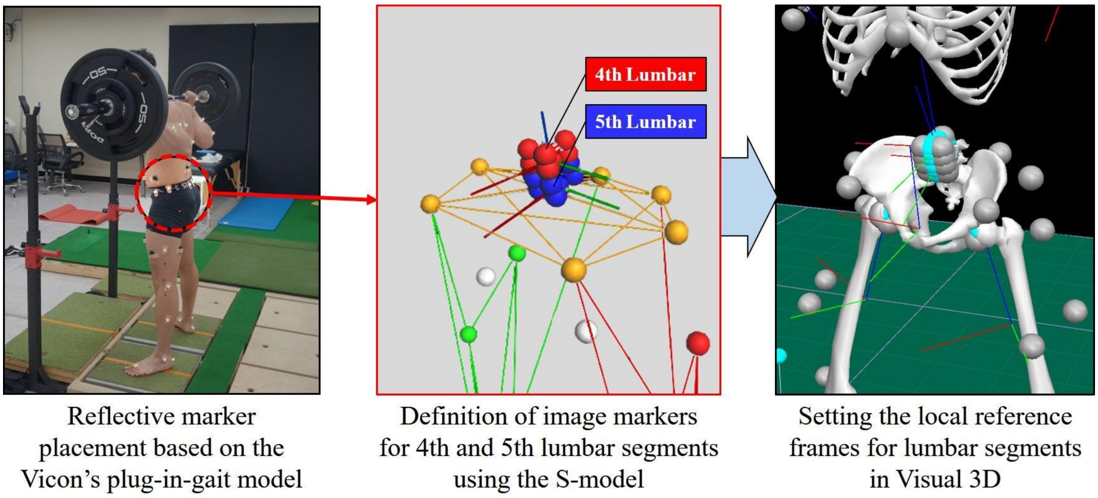

FIGURE 1. Visualization of lumbar marker estimation via S-Model.

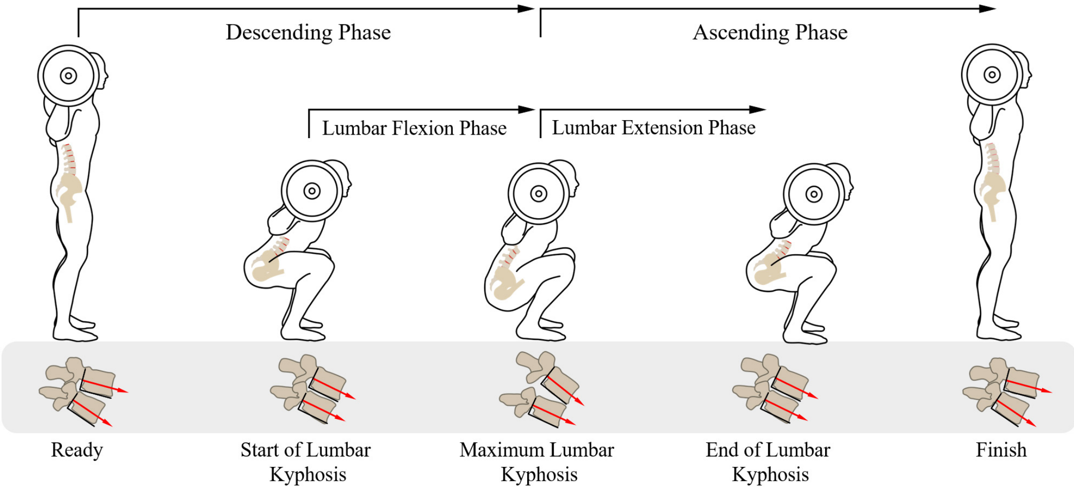

FIGURE 2. Events and phases for deep squat motion analysis. RD and FIN events are lordotic status of the 4th and 5th lumbar vertebrae. SLK and ELK events are parallel to the 4th and 5th lumbar vertebrae, and the MLK event is maximal kyphotic status of the 4th and 5th lumbar vertebrae.

TABLE 2. Definition of local reference in each direction of the lower extremity and lumbar joints.

Joints	Local reference frame		
	ML axis	AP axis	VT axis
Ankle			
+	Dorsi flexion	Inversion	IR
−	Plantar flexion	Eversion	ER
Knee			
+	Extension	Adduction	
−	Flexion	Abduction	
Hip			
+	Flexion		
−	Extension		
Lumbar			
+	Extension		
−	Flexion		

Abbreviations: ML: medial-lateral; AP: anterior-posterior; VT: vertical; IR: internal rotation; ER: external rotation.

the lower extremities, muscle activities and maximum lumbar flexion angle. Subsequently, stepwise multiple linear regression analysis was conducted to determine the most significant predictors of lumbar flexion. Statistical analyses were performed using IBM SPSS 27.0 (IBM Corp., Armonk, NY, USA), with significance set at $\alpha = 0.05$.

3. Results

3.1 Peak joint angles of the lower limbs and lumbar spine by direction and muscle activity by muscle group

To identify the biomechanical contributors to dynamic lumbar kyphosis during deep squats, peak joint angles of the ankle, knee and hip were calculated during the descending phase of the squat, along with the maximum flexion angle of the lumbar spine (Table 3). In addition, activities of key lumbar flexor and extensor muscles were measured during the lumbar flexion phase (Table 4).

3.2 Correlation between peak joint angles and muscle activity of the lower limbs and maximum lumbar flexion angle during deep squats

Pearson's correlation analysis was conducted to examine the relationships between joint angles of the lower extremities and the peak lumbar flexion angle during deep squats (Table 5). No statistically significant correlations were observed between the maximum angles of the ankle or knee joints and the lumbar flexion angle ($p > 0.05$). However, the peak hip flexion angle was significantly positively correlated with the peak lumbar flexion angle ($r = 0.590$, $p = 0.001$).

The correlation between muscle activity and peak lumbar flexion angle during deep squats was analyzed (Table 6). The lumbar flexors—RA, EO, BFL and GM—did not show a statistically significant correlation with peak lumbar flexion angle ($p > 0.05$). Among the extensors, LAT and RF also showed no significant correlation ($p > 0.05$), but ES had a significantly positive correlation with peak lumbar flexion angle ($r = 0.403$, $p = 0.027$).

3.3 Effects of lower-limb joint angles and muscle activity on peak lumbar flexion during deep squats

The effects of peak joint angles and muscle activity of the lower limbs on peak lumbar flexion during deep squats were analyzed using a stepwise multiple regression analysis (Table 7). The final model identified hip joint peak flexion angle (HJ_PFA) and erector spinae muscle activity (ES_MA) as significant predictors, and the results were significant ($r = 0.682$, adj. $R^2 = 0.426$, $p < 0.001$). Specifically, HJ_PFA ($t = 3.910$, $\beta = 0.553$, $p = 0.001$) and ES_MA ($t = 2.436$, $\beta = 0.345$, $p = 0.022$) were both found to significantly affect peak lumbar flexion. Their relationship is illustrated in Fig. 3.

4. Discussion

Dynamic lumbar kyphosis during deep squats has been identified as a contributing factor to lumbar spine injuries [15, 18, 37]. Consequently, it is imperative to establish effective strategies to prevent and address this phenomenon to ensure the safe and effective execution of deep squats. In this context, it is essential to first identify the underlying causes of dynamic lumbar kyphosis and explore evidence-based approaches for its correction. In the present study, we aimed to identify the biomechanical factors associated with dynamic lumbar kypho-

TABLE 3. Peak joint angle of the lower extremities and lumbar joints in each direction during the descending phase of the deep squat.

Joints	Direction	Mean ± SD of joint peak angle
	+/−	
Ankle (degree)		
	Dorsi flexion/Plantar flexion	30.31 ± 4.39
	Inversion/Eversion	−9.08 ± 7.03
	Internal rotation/External rotation	−7.25 ± 4.58
Knee (degree)		
	Extension/Flexion	−129.12 ± 7.53
	Adduction/Abduction	1.76 ± 4.04
	Internal rotation/External rotation	9.64 ± 6.39
Hip (degree)		
	Flexion/Extension	110.95 ± 7.99
	Adduction/Abduction	−29.14 ± 5.69
	Internal rotation/External rotation	2.25 ± 10.69
Lumbar (degree)		
	Extension/Flexion	−10.65 ± 4.13

SD: Standard deviation.

TABLE 4. Surface electromyography data of lumbar flexor/extensor muscles during the lumbar flexion phase of the deep squat.

Muscles	Mean ± SD of muscle activity
Flexor (%MVIC)	
Rectus abdominis (RA)	7.37 ± 7.24
External oblique (EO)	15.57 ± 12.95
Biceps femoris long head (BFL)	9.75 ± 5.74
Gluteus maximus (GM)	10.51 ± 7.83
Extensor (%MVIC)	
Erector spinae (ES)	31.64 ± 11.73
Latissimus dorsi (LAT)	10.52 ± 12.45
Rectus femoris (RF)	82.73 ± 43.16

MVIC: maximal voluntary isometric contraction; SD: Standard deviation.

TABLE 5. Correlation between lower extremity joint peak angles and lumbar flexion peak angles during the descending phase of the deep squat.

Variables	Lumbar peak flexion angle	
	r	*p*-value
Ankle		
Dorsi flexion	−0.021	0.912
Eversion	0.126	0.508
External rotation	−0.130	0.494
Knee		
Flexion	0.005	0.981
Adduction	0.137	0.471
Internal rotation	−0.045	0.815
Hip		
Flexion	0.590**	0.001
Abduction	0.003	0.987
Internal rotation	−0.015	0.936

Statistically significant correlations are indicated by $^{**}p < 0.01$.

TABLE 6. Correlation between surface electromyography data of lumbar flexor/extensor muscle group and lumbar peak flexion angle during the lumbar flexion phase of the deep squat.

Variables	Lumbar peak flexion angle	
	r	*p*-value
Flexor		
Rectus abdominis (RA)	−0.227	0.228
External oblique (EO)	0.062	0.743
Biceps femoris long head (BFL)	−0.215	0.254
Gluteus maximus (GM)	0.193	0.307
Extensor		
Erector spinae (ES)	0.403*	0.027
Latissimus dorsi (LAT)	0.043	0.823
Rectus femoris (RF)	−0.153	0.419

Statistically significant correlation are indicated by $^{*}p < 0.05$.

TABLE 7. Multiple linear regression analysis of the peak flexion angle of lumbar during the deep squat.

IV	Unstandardized coefficients		Standardized coefficients beta	t	p	Collinearity statistics	
	B	Std. error				Tolerance	VIF
Constant	−46.223	8.123		−5.690	0.001		
HJ_PFA	0.286	0.073	0.553	3.910**	0.001	0.989	1.011
ES_MA	0.121	0.050	0.345	2.436*	0.022	0.989	1.011
$R = 0.682$, R^2 (adj. R^2) = 0.465 (0.426)							
$F = 11.745$, $p < 0.001$							
Durbin-Watson = 2.158							

*Abbreviations: IV: independent variable; VIF: variance inflation factor; HJ_PFA: hip joint peak flexion angle; ES_MA: erector spinae muscle activity; Std. error: Standard error. *p < 0.05, **p < 0.01.*

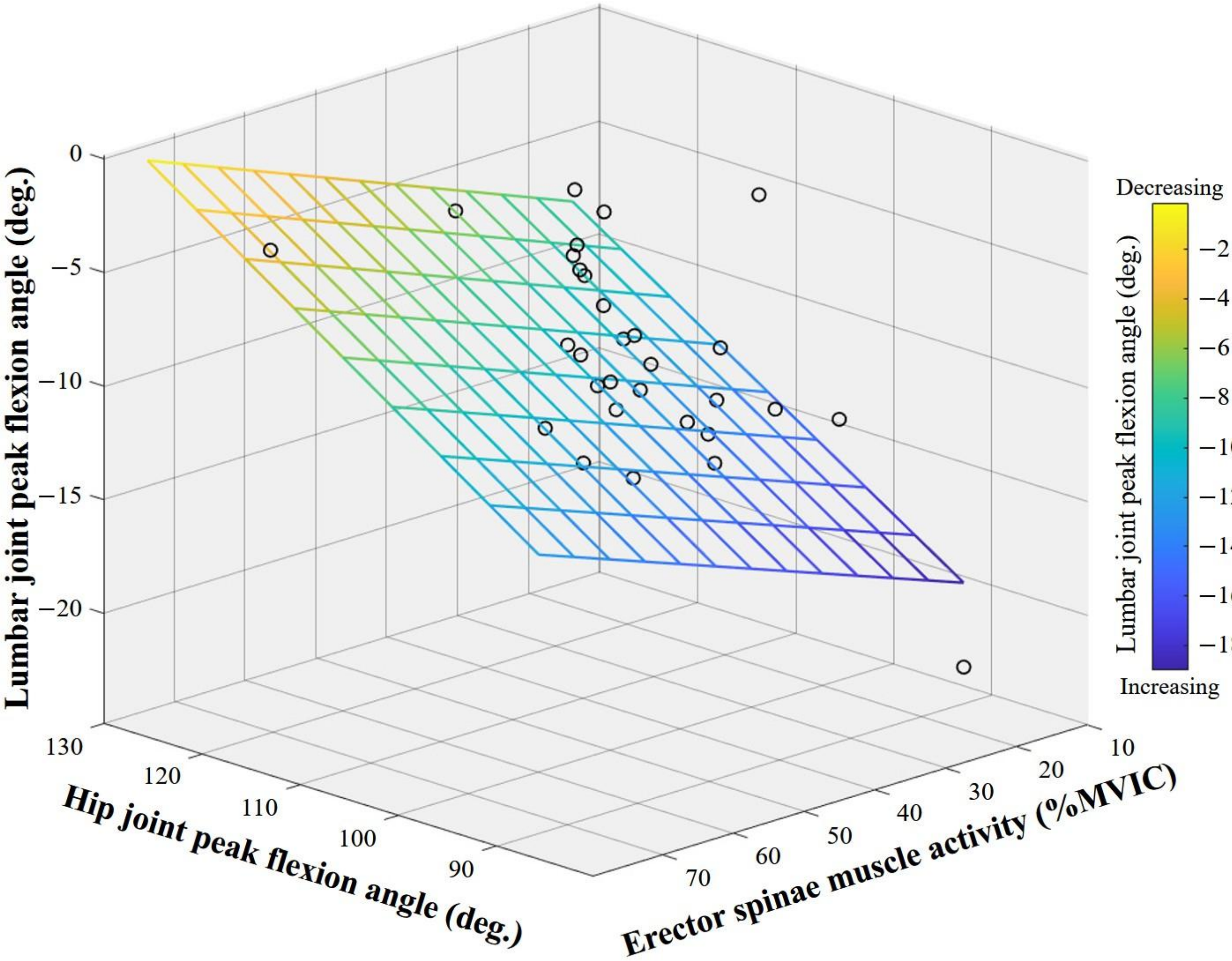

FIGURE 3. Multiple linear regression analysis illustrating the relationships between maximal lumbar flexion angle, maximal lower extremity joint angles and muscle activity during the lumbar flexion phase of a deep squat. MVIC: maximal voluntary isometric contraction; deg.: degree.

sis during deep squats by examining lower-limb joint angles and the activities of muscles involved in lumbar flexion and extension. To this end, three-dimensional motion analysis and sEMG were conducted in 30 resistance-trained adult men. The goal was to identify factors contributing to dynamic lumbar kyphosis by analyzing the peak joint angles of the ankle, knee, and hip, as well as the activities of muscles associated with lumbar flexion and extension, and evaluating their effects on the peak lumbar flexion angle.

Deep squats are typically defined as the movement in which the posterior thighs make contact with the calves, with knee flexion exceeding 120° [2, 38]. All participants in this study met this criterion, with an average maximum knee flexion angle of −129.2° during squats (Table 3). The peak lumbar flexion angle observed during squats was −10.65°, confirming the presence of dynamic lumbar kyphosis in all participants (Table 3). The deep squat is a closed-chain, multi-joint movement that involves a greater ROM in the lower extremities compared to other squat variations. Proper execution requires multiple physical capacities, with lower-limb joint mobility and muscle function playing key roles in maintaining control and alignment throughout the movement. Limited joint ROM (mobility) may lead to compensatory movement patterns, negatively affecting joint alignment and postural stability [6, 8, 23, 39]. In addition, lumbar flexion and extension during a deep squat are governed by the coupling forces between agonist and antagonist muscles [12]. Based on this, we anticipated that the degree of dynamic lumbar kyphosis is likely influenced by the activities of muscles involved in lumbar control. Thus, we hypothesized that lower-limb mobility and the activity of key muscles responsible for lumbar motion would be associated with dynamic lumbar kyphosis.

We analyzed the correlations between peak joint angles and muscle activity with peak lumbar flexion angles, followed by stepwise regression to determine their predictive value. The results revealed significant positive correlations between the peak hip flexion angle, erector spinae activity and peak lumbar flexion angle during deep squats. Specifically, greater hip flexion and higher erector spinae activity were associated with reduced lumbar flexion, suggesting that lumbar flexion decreases with increasing erector spinae activity. Stepwise multiple regression analysis further identified both peak hip flexion angle and erector spinae activity as significant predictors of peak lumbar flexion angle, with hip mobility exerting a stronger influence than erector spinae activity. These findings suggest that limited hip mobility and decreased erector spinae activity may contribute to dynamic lumbar kyphosis (Table 7). Consequently, targeted interventions addressing these factors may be effective in its prevention and correction.

During the descent phase of the deep squat, hip flexion is crucial for facilitating proper movement mechanics [6, 37]. Limited hip flexion mobility not only restricts proper squat depth but also leads to decreased lumbar extensor strength and increased lumbar flexion, often resulting in excessive forward trunk lean [8, 40]. The present study also confirmed that greater hip mobility was associated with reduced dynamic lumbar kyphosis. These results underscore the importance of adequate hip flexion ROM in controlling lumbar alignment during deep squats. The erector spinae also play a key role in regulating lumbar extension and protecting the spine from excessive flexion [37, 41]. Previous studies have reported a tendency for erector spinae activation to decrease when the lumbar spine enters a flexed posture [42, 43], which may compromise the maintenance of a neutral alignment. Functionally, the erector spinae generate lumbar extensor torque and resists excessive forward bending [12, 44, 45]. The findings of this study also suggest that lower erector spinae activity during deep squats is associated with reduced control of lumbar flexion, thereby contributing to greater dynamic lumbar kyphosis. Therefore, erector spinae activity appears to be a key factor in both preventing and correcting dynamic lumbar kyphosis during deep squats.

In summary, this study identified limited hip flexion mobility and reduced erector spinae activation as key contributors to dynamic lumbar kyphosis during deep squats. To mitigate this compensatory movement, training programs should incorporate exercises that improve hip flexion ROM and strengthen the erector spinae. Such targeted interventions may help prevent and effectively reduce dynamic lumbar kyphosis during deep squat performance. However, as all participants in this study were male, the generalizability of the findings to female populations is limited. Therefore, future research should investigate dynamic lumbar kyphosis during deep squats in female participants. Additionally, based on the present findings, it is necessary to develop training interventions aimed at improving dynamic lumbar kyphosis during deep squats and to evaluate their effectiveness through empirical studies.

5. Conclusions

In this study, we aimed to identify the biomechanical factors contributing to dynamic lumbar kyphosis during deep squats and determine key variables for its prevention. The results revealed that hip peak flexion angle and erector spinae activity significantly predicted the degree of lumbar flexion, with hip mobility playing a particularly important role in mitigating dynamic lumbar kyphosis. Higher erector spinae activity was also associated with reduced lumbar flexion, suggesting that increased engagement of this muscle group, which serves as one of the core muscles responsible for stabilizing and controlling body movement, may help minimize excessive spinal curvature during the movement through the coordinated activation of the core muscle group. Accordingly, improving hip mobility and enhancing erector spinae function are essential for preventing dynamic lumbar kyphosis during deep squats. Training programs should incorporate mobility and stretching exercises targeting the hip joint, along with resistance exercises aimed at strengthening the erector spinae.

AVAILABILITY OF DATA AND MATERIALS

The data presented in the results of this paper will be made available by the authors upon request.

AUTHOR CONTRIBUTIONS

JL and MK—conceptualization; methodology; formal analysis, investigation, writing-review and editing, supervision; data curation. JL, YL and MK—original draft writing; review and editing. All authors participated in the review and agreed to publish the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Institutional Review Board of Konkuk University (IRB No. 7001355-202204-HR-543) and adhered to the Declaration of Helsinki. The participants in the experiment were adequately informed about the purpose, risks and procedures of the study and signed a consent form.

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Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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