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Research article

Effects of Changing Center of Pressure Position on Knee and Ankle Extensor Moments During Double-Leg Squatting

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Abstract

The effects of changes in the anterior-posterior center of pressure (AP-COP) position on the lower limb joint moments during double-leg squatting remain unclear. The purpose of this study was to determine the effects of AP-COP positional changes on the hip, knee, and ankle extensor moments during double-leg squatting. Sixteen male participants (22.1 ± 1.5 years) performed double-leg squatting under two conditions (anterior and posterior COP conditions) with visual feedback on their COP positions. Kinematics and kinetics were analyzed using a three-dimensional motion analysis system and force plates. The hip, knee and ankle flexion angles and extensor moments at peak vertical ground reaction force were compared between the two conditions using paired t tests. The COP position was 53.5 ± 2.4% of the foot length, starting from the heel, under the anterior condition and 44.4 ± 2.1% under the posterior condition ($P < 0.001$). The knee extensor moment was significantly smaller under the anterior than the posterior COP condition ($P = 0.003$, 95% confidence interval (CI) -0.087 to -0.021 Nm/kg/m), while the ankle extensor moment significantly larger under the anterior COP condition than under the posterior COP condition ($P < 0.001$, 95% CI 0.113 to 0.147 Nm/kg/m). There was no significant difference in hip extensor moment ($P = 0.431$). The ankle dorsiflexion angle was significantly larger under the anterior than the posterior COP condition ($P = 0.003$, 95% CI 0.6 to 2.6°), while there was no difference in trunk, hip, or knee flexion angle. The present results indicate that changes in the AP-COP position mainly affect the ankle and knee extensor moments during double-leg squatting, while the effect on the lower limb joint and trunk flexion angles was limited. Visual feedback on the AP-COP position could be useful for modifying the ankle and knee extensor moments during double-leg squatting.

Key words: Biomechanics, visual feedback, exercise, strength, COP.

Introduction

Squatting exercises are widely used in sports and rehabilitation to enhance lower-limb muscle strength and are performed using multiple lower limb joints (Schoenfeld, 2010). Based on the aim of training and symptoms of patients, hip, knee and ankle extensor moments are coordinated to enhance the effects of training while minimizing the risk of worsening symptoms and iatrogenic injury (Chan and Sigward, 2020; Kernozek et al., 2018; Roos et al., 2014; Salem et al., 2003; Sigward et al., 2018; Straub et al., 2021; Webster et al., 2015). For example, patients with patellofemoral pain syndrome should coordinate their knee extensor moments to decrease patellofemoral joint stress during squatting exercises (Kernozek et al., 2018). Patients with patellar and Achilles tendinopathy also need to coordinate their knee and ankle extensor moment to manage tendon loading according to their symptoms (Martin et al., 2018; Núñez-Martínez and Hernández-Guillen, 2021; Rosen et al., 2021; Silbernagel et al., 2020). After anterior cruciate ligament reconstruction, patients should increase the knee extensor moment to address compensatory high hip and ankle extensor moments for return to sports (Chan and Sigward, 2020; Roos et al., 2014; Salem et al., 2003; Sigward et al., 2018; Webster et al., 2015).

Trunk flexion, anterior-posterior knee positioning, shank inclination and the ankle dorsiflexion angle have been widely studied for their effects on the knee extensor moment, patellofemoral joint stress and anterior tibial force during double-leg squatting (Biscarini et al., 2011; Fry et al., 2003; Kernozek et al., 2018; Lorenzetti et al., 2012; Straub et al., 2021). Greater trunk flexion decreases the knee extensor moment (Biscarini et al., 2011; Straub et al., 2021), and restriction of anterior knee shifting decreases the knee extensor moment and increases the hip extensor moment (Fry et al., 2003; Lorenzetti et al., 2012; Straub et al., 2021). On the other hand, a few studies reported that the anterior-posterior center of pressure (AP-COP) is also associated with lower limb joint moment coordination during squatting, showing that side-to-side differences in the AP-COP position were associated with those in the ankle extensor moment during double-leg squatting (Flanagan and Salem, 2007) and that the AP-COP position predicted hip-to-knee and ankle-to-knee extensor moment ratios for patients after anterior cruciate ligament reconstruction (Chan and Sigward, 2020). Recently, maximal intentional anterior COP positional shifts were shown to decrease quadriceps muscle activities but increase gastrocnemius muscle activity during double-leg squatting (Kitamura et al., 2019). On the other hand, Kernozek et al. (2018) showed that squatting with limited anterior knee translation was associated with a smaller knee extensor moment and a more posterior COP position. Therefore, it is unclear whether an intentional shifting of the COP position can alter the lower limb joint moments. Real-time visual feedback regarding patellofemoral forces during squatting decreased patellofemoral joint forces and knee extensor moments (Kernozek et al., 2020). Feedback about the AP-COP position can be provided using a force plate, which would be easily understood by patients and athletes. Thus, changing the lower limb joint moments by shifting the AP-COP position is considered to have potential for wide clinical application.

The purpose of the present study was to determine the effects of AP-COP positional changes using visual

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feedback on hip, knee, and ankle extensor moments during double-leg squatting. The hypothesis was that an anterior COP condition would result in larger hip and ankle extensor moments but a smaller knee extensor moment than a posterior COP condition.

Methods

Participants

An a priori sample size calculation was conducted to detect differences in lower limb extensor moments with an effect size (d_z) of 0.80 based on previous studies (Chan and Sigward, 2020; Kitamura et al., 2019), and the results showed that a total of 15 participants were needed to achieve an alpha level and statistical power of 0.05 and 0.8, respectively. Sixteen male participants were enrolled in the study (age 22.1 ± 1.5 years, height 170.5 ± 4.6 cm, body weight 63.3 ± 8.4 kg). Participants were excluded from this study if they reported pain during double-leg squatting, any history of a musculoskeletal injury within the prior 6 months, or surgery on the lower extremities or trunk. Written informed consent was obtained from each participant before participation. This study was approved by the Institutional Review Board of Faculty of Health Sciences, Hokkaido University (approval number: 21-59).

Procedures and data collection

A three-dimensional motion analysis system (Cortex version 5.0.1, Motion Analysis Corporation, Santa Rosa, CA, USA) was used to record marker coordinates and force data with seven cameras (Hawk cameras, Motion Analysis Corporation) and two force plates (Type 9286, Kistler AG, Winterthur, Switzerland). The sampling rates were set at 200 Hz for the marker coordinate data and at 1,000 Hz for the force plate data.

Participants warmed up for five-minutes using a bicycle ergometer at a self-selected pace. Then, a total of 38 markers were placed on the iliac crest, anterior and posterior superior iliac spines (ASISs and PSISs, respectively), medial and lateral femoral epicondyles, medial and lateral malleoli, second metatarsal head and base, fifth metatarsal head and heel. Additionally, marker clusters were attached to the lateral thigh and shank. Following a static standing trial, participants performed a double-leg squatting task under two COP conditions. First, the participant's feet were positioned on the individual force plates shoulder-width apart, and the toe tips were aligned with the predetermined position on each force plate to provide real-time feedback about the COP position for each foot. The participants crossed their arms over their chest. Participants were instructed to squat with their thighs parallel to the floor without their heels coming off the floor and then stand upright.

The AP-COP position was represented as the percentage of foot length (% foot length) from the heel (0%) to the toe (100%) (Chan and Sigward, 2020). For clinical practicality, the toe angle of each participant was not considered (Figure 1). The two COP conditions were conducted with real-time visual feedback regarding the AP-COP position for each foot (Figure 2) as follows: 1) anterior COP condition: squatting while keeping the AP-COP position within 55 ± 2.5% of the foot length from the heel during the descent phase (Figure 2a); 2) posterior COP condition: squatting while keeping the AP-COP position within 45 ± 2.5% of the foot length from the heel during the descent phase (Figure 2b). These two COP conditions were set by considering the mean and side-to-side difference in the AP-COP position for healthy individuals and patients after anterior cruciate ligament reconstruction (Chan and Sigward, 2020; Flanagan and Salem, 2007; Kitamura et al., 2019). The real-time AP-COP position on each side was displayed on a 27-inch monitor using LabVIEW (version 21, National Instruments Corp., Austin, TX, USA). The monitor was placed 1 m in front of the participant's toes, and the height was adjusted according to each participant's preference (Figure 2c). The AP-COP position was displayed as a bar graph in the range from 20 to 80% of the foot length. An increase in the bar indicated that the COP moved anteriorly, while a decrease in the bar indicated that the COP moved posteriorly. Familiarization with each COP condition was obtained with six sets of five consecutive squats. Then, three sets of five consecutive squats for each COP condition were recorded, and analysis was performed on the average of the middle three squats in the five consecutive squats of the three sets (Sigward et al., 2018).

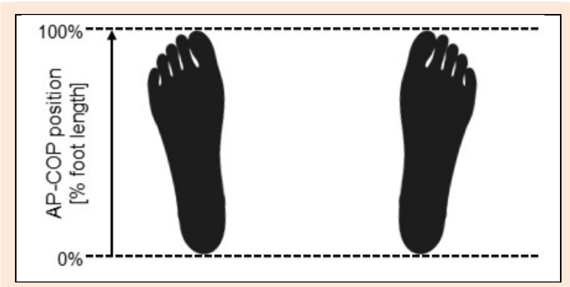

Figure 1. Definition of the anterior-posterior center-of-pressure (AP-COP) position.

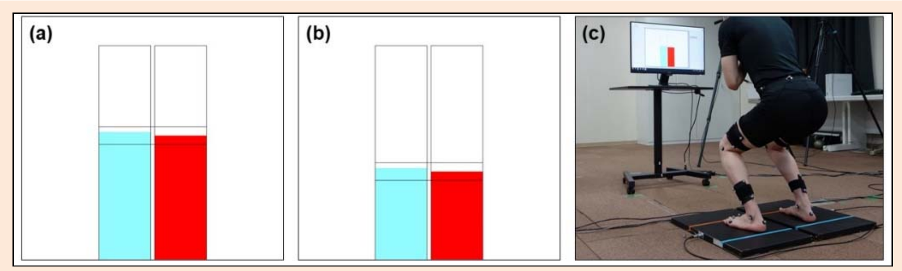

Figure 2. Real-time feedback regarding the center of pressure (COP) position under the (a) anterior COP condition and (b) posterior COP condition. The left and right bars indicate the anterior-posterior COP position of the left and right foot, respectively.

Data processing and reduction

Analysis was performed on the dominant leg of each participant, which was defined as the leg preferred for kicking a ball. Biomechanical analysis was performed using Visual3D (version 6, C-Motion, Inc, Germantown, MD, USA) and MATLAB (MathWorks, Natick, MA, USA). A low-pass filter using a fourth-order zero-lag Butterworth filter with a cutoff frequency of 12 Hz was applied to the marker trajectory and force plate data (Chan and Sigward, 2020; Sigward et al., 2018). The gaps in the ASIS marker trajectory due to hip flexion were filled using the iliac crest and PSIS markers (McClelland et al., 2010; Webster et al., 2015). Lower limb joint angles and moments were calculated using a joint coordinate system with the Cardan sequence (i.e., flexion/extension is the first). Trunk flexion was expressed relative to the laboratory coordinate system using the *Z-Y-X* sequence (i.e., flexion/extension is the last) (Baker, 2001). The internal moments of the lower limb joints were determined using inverse dynamics with the segment's inertial properties based on a previous report (de Leva, 1996). The COP position was calculated according to the manufacturer's instructions, as follows:

$$\mathbf{COPx} = -My/Fz$$
$$\mathbf{COPy} = Mx/Fz$$

where My represents the plate moment about the Y-axis, Mx represents the plate moment about the X-axis, and Fz represents the vertical ground reaction force (VGRF).

The hip, knee and ankle flexion angles and internal extensor moments and AP-COP position were derived at the peak VGRF for the dominant leg (Chan and Sigward, 2020). In addition, the three lower limb joint extensor moment ratios were calculated to assess the hip, knee and ankle moment contributions as percentages of the total support moment (i.e., hip-to-total, knee-to-total, and ankle-to-total support moment ratios) (Roos et al., 2014). The total support moment was calculated as the sum of the hip, knee and ankle extensor moments. The VGRF was normalized to each participant's body weight (N/kg), and joint moments were normalized to each participant's body weight and height (Nm/kg/m) (Derrick et al., 2020). All variables were averaged across the middle three descent phases of the three trials (Sigward et al., 2018).

Statistical analysis

All data are presented as the mean and standard deviation (SD). A paired t test was used to confirm the kinematic and kinetic differences between the anterior and posterior COP conditions. The effect size was also calculated for each pairwise comparison with d_z (Faul et al., 2007). The statistical significance level was set at $P < 0.05$. These statistical analyses were performed using IBM SPSS Statistics software (version 22, IBM Corporation, Armonk, NY, USA).

Results

The COP position at the peak VGRF was significantly different between the anterior and posterior COP conditions ($P < 0.001$) (Table 1). However, there was no significant difference in the peak VGRF between the two conditions (Table 1).

The COP condition significantly affected the knee and ankle extensor moments at the peak VGRF (Figure 3). The knee extensor moment was significantly smaller under the anterior COP condition than under the posterior COP condition (anterior condition: 0.818 ± 0.179 Nm/kg/m, posterior condition: 0.872 ± 0.169 Nm/kg/m, $P = 0.003$, 95% CI -0.087 to -0.021 Nm/kg/m, $d_z = -0.888$), while the ankle extensor moment was significantly larger under the anterior COP condition than under the posterior COP condition (anterior condition: 0.432 ± 0.045 Nm/kg/m, posterior condition: 0.302 ± 0.037 Nm/kg/m, $P < 0.001$, 0.95% CI 0.113 to 0.147 Nm/kg/m, $d_z = 4.173$) (Figure 3). On the other hand, no significant difference was found in the hip extensor moment between the two conditions (anterior condition: 0.687 ± 0.151 Nm/kg/m, posterior condition: 0.677 ± 0.135 Nm/kg/m, $P = 0.431$, 95% CI −0.017 to 0.037 Nm/kg/m, $d_z = 0.212$). Thus, the ratio of the knee extensor moment to the total support moment was significantly smaller under the anterior COP condition than under the posterior COP condition (anterior condition: 42.1 ± 7.4%, posterior condition: 47.0 ± 7.8%, $P < 0.001$, 95% CI -5.8 to -4.0% total support moment, $d_z = -2.897$), while the ratio of the ankle extensor moment to the total support moment was significantly larger under the anterior COP condition than under the posterior COP condition (anterior condition: 22.4 ± 2.2%, posterior condition: 16.4 ± 1.9%, $P < 0.001$, 95% CI 5.1 to 6.8% total support moment, $d_z = 3.792$) (Figure 4). The hip extensor moment contribution was also significantly smaller under the anterior COP condition (anterior condition: 35.5 ± 7.4%, posterior condition: 36.6 ± 7.1%, $P = 0.015$, 95% CI: -1.9 to -0.2, $d_z = -0.702$). A significant difference in joint angles was found only for the ankle dorsiflexion angle (Table 2).

Table 1. **Kinetic comparison of the anterior and posterior COP conditions. Data are means (±SD).**

	Anterior COP condition	Posterior COP condition	95% CI	*P* value	ES [d_z]
VGRF, N/kg	5.63 (0.38)	5.60 (0.35)	−0.06 to 0.12	0.472	0.188
COP position, % foot length	53.0 (1.8)	43.3 (1.7)	9.0 to 10.5	**< 0.001**	6.986

COP: center of pressure; ES: effect size; VGRF: vertical ground reaction force

Table 2. **Kinematic comparison of the anterior and posterior COP conditions. Data are means (±SD).**

	Anterior COP condition	Posterior COP condition	95% CI	*P* value	ES [d_z]
Trunk flexion angle, deg	39.5 (13.1)	38.8 (11.9)	−0.9 to 2.3	0.357	0.259
Hip flexion angle, deg	87.5 (9.1)	89.3 (6.7)	−4.3 to 0.7	0.154	−0.352
Knee flexion angle, deg	93.9 (44.5)	95.9 (10.7)	−5.0 to 1.0	0.182	−0.427
Ankle dorsiflexion angle, deg	19.8 (5.9)	18.2 (5.4)	0.6 to 2.6	**0.003**	0.918

COP: center of pressure; ES: effect size

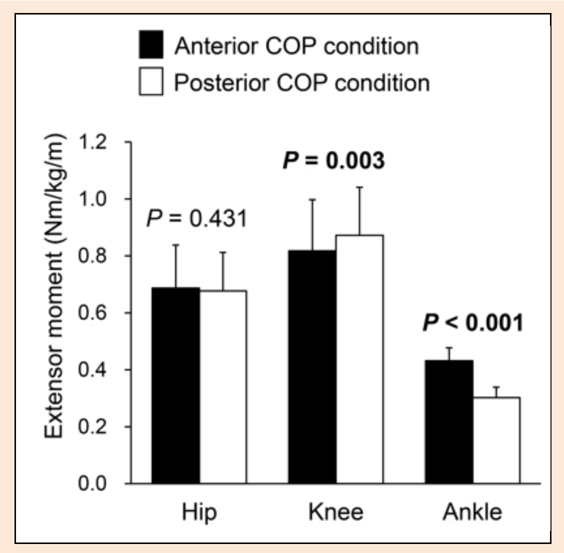

Figure 3. Comparison of the hip, knee and ankle extensor moments between the anterior and posterior center of pressure (COP) conditions. Error bars indicate one standard deviation.

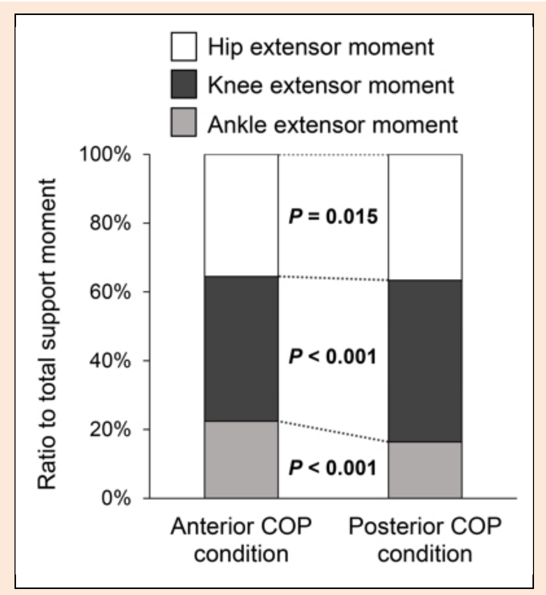

Figure 4. Comparison of the hip, knee and ankle extensor moment contributions between the anterior and posterior center of pressure (COP) conditions.

Discussion

The present study revealed that change in the COP position affects the ankle and knee extensor moments during double-leg squatting, while no effect on the hip extensor moment was observed under the COP conditions used in this study. These findings partially support our a priori hypotheses.

The AP-COP position was significantly different between the anterior and posterior COP conditions, and the mean positions were within the target range for each condition. Thus, the conditions set in this study were properly performed. However, there was no significant difference in the VGRF, or trunk, hip or knee flexion angle. The ankle dorsiflexion angle was significantly larger under the anterior COP condition, while the mean difference was only 1.6°. Thus, the present findings on the difference in lower-limb joint moment were caused by the change in AP-COP position.

The ankle extensor moment was significantly larger under the anterior COP condition than under the posterior COP condition. This finding is supported by a previous study showing that side-to-side differences in the ankle extensor moment were significantly associated with side-to-side differences in the distance between the COP and ankle joint center during double-leg squatting (Flanagan and Salem, 2007). Moreover, an electromyography study showed that the muscle activity of the gastrocnemius lateral head was increased during double-leg squatting with the COP shifted anteriorly as far as possible, which also supports the present finding (Kitamura et al., 2019). It is interesting for the present study that the decrease in the AP-COP position of 9.1% of the foot length led to a decrease in the ankle extensor moment of approximately 30%. The contribution of the ankle extensor moment to the total support moment changed by approximately 6%. These results indicate that the AP-COP position and ankle extensor moment are closely related. The AP-COP position is a good indicator of the ankle extensor moment during squatting.

The knee extensor moment was significantly smaller under the anterior COP condition than under the posterior COP condition. Trunk flexion and anterior-posterior knee position (or shank inclination) are well studied as indicators of the knee extensor moment (Biscarini et al., 2011; Fry et al., 2003; Kernozek et al., 2018; Lorenzetti et al., 2012; Straub et al., 2021). The present finding adds the AP-COP position as a new indicator of the knee extensor moment. The decrease in the knee extensor moment under the anterior COP condition compared to the posterior COP condition was approximately 6%, and the ratio of the knee extensor moment to the total support moment decreased by approximately 5%. Although direct comparisons cannot be made because of the different reference conditions of the comparison, the decrease in the present study may be smaller than that in the previous studies showing that restriction of the anterior knee displacement causes an approximately 20% decrease in the knee extensor moment (Fry et al., 2003; Kernozek et al., 2018). On the other hand, a previous study showed that an increase in vastus medialis activity of approximately 60% during double-leg squatting with the AP-COP shifted from approximately 45% to 75% of the foot length (Kitamura et al., 2019). Therefore, a larger change in the AP-COP position than in the present study may alter the knee extensor moment more, but additional research is needed to prove this hypothesis.

The effect of the AP-COP position on the hip extensor moment was not apparent in the present study. The contribution of the hip extensor moment was significantly different between the anterior and posterior COP conditions, though the mean difference between the two conditions was approximately 1%. This small difference in the contribution of the hip extensor moment could be attributed to changes in the ankle and knee extensor moments because there was no significant difference in the magnitude of the hip extensor moment between the two conditions. It is thought that the ankle and knee extensor moments are related to the AP-COP position through the changes in the moment arms of the ankle and knee joints (Chan and Sigward, 2020; Flanagan and Salem, 2007). Thus, the difference in the AP-COP position of 9.1% of the foot length between the two conditions had no effect on the hip extensor moment in the present study because the hip joint positions are higher than the knee and ankle joints. Further studies are needed to investigate the effect of larger changes in the AP-COP position on the hip extensor moment than those used in the present study.

This study showed that the AP-COP position could coordinate the ankle and knee extensor moments. Trunk flexion and anterior-posterior knee position have been widely used as indicators of the knee extensor moment (Biscarini et al., 2011; Fry et al., 2003; Kernozek et al., 2018; Lorenzetti et al., 2012; Straub et al., 2021). Compared with these variables, the AP-COP position is characterized by usability, as a feedback variable with real-time and continuous numbers determined using a force plate. The participants of the present study were able to control the COP position within the target range. Moreover, after anterior cruciate ligament reconstruction, patients showed a smaller knee-to-ankle extensor moment ratio in the involved limb than in the uninvolved limb during double-leg squatting (Chan and Sigward, 2020). This previous study also reported a more anterior COP position in the involved limb than the uninvolved limb and the association between the interlimb ratio for the knee-to-ankle extensor moment ratio and AP-COP position. On the other hand, the side-to-side difference in the ankle flexion angle was approximately 3° or not found in patients after anterior cruciate ligament reconstruction (Roos et al., 2014; Salem et al., 2003). The trunk flexion angle cannot be used to assess side-to-side differences. Therefore, training with visual feedback on the AP-COP position may be useful to improve the interlimb asymmetry in the knee-to-ankle extensor moment ratio during double-leg squatting in patients after anterior cruciate ligament reconstruction. Although little attention has been given to coordination of the ankle extensor moment during squatting, the ankle extensor moment under the anterior COP condition was comparable to that during the double-leg heel raise (Flanagan et al., 2005).

The present study has some limitations that should be acknowledged. First, double-leg squatting was performed without external resistance. The magnitude of the effect of the AP-COP position on lower limb joint moment may be different when squatting with and without an external resistance. Second, it is unclear how much effect there is when the AP-COP position is varied beyond the range used in the present study. Further knowledge should be accumulated on performing squatting exercises while receiving feedback on the AP-COP position. Finally, the present study controlled only the COP position, and no difference in kinematics was observed. Feedback on the trunk flexion and AP knee position are widely used to adjust the knee extensor moment, while the effect of changing the AP-COP position in combination with kinematic coordination is unclear.

Conclusion

The present study showed significant differences in the ankle and knee extensor moments when double-leg squatting under anterior and posterior COP conditions. The anterior COP condition was associated with a significantly larger ankle extensor moment but a smaller knee extensor moment than the posterior COP condition. These findings indicate that the ankle and knee extensor moments during double-leg squatting can be coordinated using visual feedback on the AP-COP position.

Acknowledgements

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Key points

- This study analyzed lower limb joint moment during double-leg squatting under two conditions to determine the effect of the center-of-pressure position on lower-limb joint moment.
- A difference in the anterior-posterior center-of-pressure position of ~10% of foot-length changed the ankle extensor moment by 30% and the knee extensor moment by 6%.
- No significant difference in the hip extensor moment between the two conditions.
- The knee and ankle extensor moments during double-leg squatting can be coordinated by visual feedback about the anterior-posterior center-of-pressure position.

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