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*original research*

# Altered Knee and Ankle Kinematics During Squatting in Those With Limited Weight-Bearing–Lunge Ankle-Dorsiflexion Range of Motion

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***Context:*** Ankle-dorsiflexion (DF) range of motion (ROM) may influence movement variables that are known to affect anterior cruciate ligament loading, such as knee valgus and knee flexion. To our knowledge, researchers have not studied individuals with limited or normal ankle DF-ROM to investigate the relationship between those factors and the lower extremity movement patterns associated with anterior cruciate ligament injury.

***Objective:*** To determine, using 2 different measurement techniques, whether knee- and ankle-joint kinematics differ between participants with limited and normal ankle DF-ROM.

***Design:*** Cross-sectional study.

***Setting:*** Sports medicine research laboratory.

***Patients or Other Participants:*** Forty physically active adults (20 with limited ankle DF-ROM, 20 with normal ankle DF-ROM).

***Main Outcome Measure(s):*** Ankle DF-ROM was assessed using 2 techniques: (1) nonweight-bearing ankle DF-ROM with the knee straight, and (2) weight-bearing lunge (WBL). Knee flexion, knee valgus-varus, knee internal-external rotation, and ankle DF displacements were assessed during the overhead-squat, single-legged squat, and jump-landing tasks. Separate 1-way analyses of variance were performed to determine whether differences in knee- and ankle-joint kinematics existed between the normal and limited groups for each assessment.

***Results:*** We observed no differences between the normal and limited groups when classifying groups based on nonweight-bearing passive-ankle DF-ROM. However, individuals with greater ankle DF-ROM during the WBL displayed greater knee-flexion and ankle-DF displacement and peak knee flexion during the overhead-squat and single-legged squat tasks. In addition, those individuals also demonstrated greater knee-varus displacement during the single-legged squat.

***Conclusions:*** Greater ankle DF-ROM assessed during the WBL was associated with greater knee-flexion and ankle-DF displacement during both squatting tasks as well as greater knee-varus displacement during the single-legged squat. Assessment of ankle DF-ROM using the WBL provided important insight into compensatory movement patterns during squatting, whereas nonweight-bearing passive ankle DF-ROM did not. Improving ankle DF-ROM during the WBL may be an important intervention for altering high-risk movement patterns commonly associated with noncontact anterior cruciate ligament injury.

***Key Words:*** knee flexion, knee valgus, knee varus, anterior cruciate ligament, squat, jump landing

**Key Points**

- Nonweight-bearing ankle-dorsiflexion range of motion was not associated with changes in ankle or knee kinematics during the overhead-squat, single-legged squat, or jump-landing task.
- Greater ankle-dorsiflexion range of motion during the weight-bearing lunge resulted in greater sagittal-plane motion at the knee and ankle during the squatting tasks but not the jump landing.
- Compared with nonweight-bearing passive measures, ankle-dorsiflexion range of motion during the weight-bearing lunge may be a more sensitive measure for identifying those with high-risk movement patterns.

An estimated 350 000 anterior cruciate ligament (ACL) reconstructions are performed annually in the United States,[1] with most of those injuries occurring during sport participation by individuals between 15 and 25 years old.[2,3] Recent estimates have illustrated a national increase in ACL injuries of 67.8% during a 10-year period.[4] In addition to those concerning numbers, 70% of ACL injuries result from *noncontact mechanisms*, defined as no contact with another player or piece of equipment, such as plant-and-cut maneuvers, landing from a jump, and decelerating.[5,6] The high incidence of noncontact ACL injury is driving researchers to investigate possible biomechanical and neuromuscular factors that may contribute to ACL injury.

Dynamic maneuvers, such as the overhead-squat (OHS),[7] single-legged squat (SLS),[8] and jump-landing (JL)[9] tasks, have been used in laboratory and clinical settings to elucidate faulty lower extremity movement patterns and to identify individuals potentially at risk for ACL injury. Some of the key patterns of movement identified are side-to-side (frontal-plane) or rotational (transverse-plane) movements at the knee because those movements place the greatest load on the ACL in combination with an anterior tibial shear force (sagittal plane).[10] Anterior cruciate ligament loading is exacerbated when the knee is in a minimally flexed or hyperextended position in conjunction with a large quadriceps muscle contraction.[11,12] Noncontact ACL injury mechanisms are often described as landing in a relatively extended knee position (sagittal plane) combined with frontal- and transverse-plane loading.[12] Movement at adjacent joints also influences knee loading. Researchers[7,13,14] have identified a potential relationship between limited dorsiflexion range of motion (DF-ROM) in the ankle and knee kinematics, such as medial knee displacement, which may increase the risk of ACL injury. Ideally, those squatting and JL movements would include primarily sagittal-plane motion at all lower extremity joints to perform properly and absorb and dissipate the landing forces.[15] Restrictions in the ability to move through ankle DF during weight bearing can interfere with performance by potentially increasing the plantar-flexion moment when the ankle is dorsiflexed[16] and restricting the forward rotation of the shank at the ankle when the foot is in contact with the ground.[17] Limitations in ankle-DF displacement are often accompanied by less sagittal-plane motion at proximal joints, such as the knee and trunk.[15,18] Therefore, ankle-DF restrictions may contribute to limited sagittal-plane motion at the knee and thereby contribute to compensatory increases in frontal- and transverse-plane motions that are potentially injurious to the ACL.

Less DF-ROM assessed passively in a nonweight-bearing (NWB) position has been associated with greater medial-knee displacement during a variety of tasks.[7,14] Bell et al[7] studied individuals with medial-knee displacement, which is a clinical observation of dynamic valgus collapse, and observed that participants who displayed medial-knee displacement during an OHS had approximately 20% less NWB, passive ankle DF than did those participants without medial-knee displacement. Furthermore, the medial-knee displacement observed during the OHS was corrected when a 2-in (5.08-cm) lift was placed under the heel; the correction may have occurred because of the increased tibial angle in the anterior direction. Less passive DF-ROM assessed in NWB movements has also been associated with greater frontal-plane knee excursion during a double-legged drop-landing in young female soccer players[14] and with decreased knee-flexion displacement during a jump-landing task.[19]

Other authors have investigated ankle-DF motion during dynamic movements in relation to knee kinematics, with contrasting findings. Compared with men, women with greater DF-ROM measured during SLS[20] and double-legged drop landings[21] demonstrated greater maximum knee-valgus angles. This body of research suggests that ankle DF-ROM may contribute to the amount of knee valgus (frontal plane) and knee flexion (sagittal plane) an individual uses during dynamic movement, but the relationship is unclear and requires further investigation.

Previous examinations[7,14,19] of the relationship between ankle DF-ROM and knee kinematics may be limited because of the NWB, passive assessments that were often used. Weight-bearing measures of ankle DF-ROM may provide a better representation of the available ROM during functional, weight-bearing tasks.[22] However, previous authors have not, to our knowledge, investigated the relationship between knee kinematics during dynamic movement and separate weight-bearing and NWB ankle DF-ROM assessments. In addition, no previous researchers, to our knowledge, have intentionally recruited a participant population with known limitations in ankle DF-ROM. Therefore, the purpose of our study was to investigate knee and ankle kinematics during dynamic tasks in participants who were identified as having limited ankle DF-ROM and to compare the results with those of participants who had normal ankle DF-ROM. Ankle-DF motion was assessed passively through both weight-bearing and NWB techniques before testing, and total displacement during dynamic movement was calculated. The goal of comparing the ROM of normal and limited groups was to find an assessment that could be used clinically to indicate how an individual will perform during a more functional task. We hypothesized that individuals with less DF-ROM, both NWB and weight bearing, would display kinematics associated with ACL loading (less sagittal-plane motion and greater frontal-plane motion) during an OHS, SLS, and JL task.

## METHODS

### Participants

Initial group allocation was determined through a screening process performed by the primary researcher (K.E.D.) using an NWB measure of passive ankle DF-ROM with the knee extended. We chose this measurement for participant recruitment because we had identified cutoff angles derived from Moseley et al,[17] based on their data classifying individuals as normal (11.2°–25.0°) or inflexible (4.3°–11.2°). We wanted a clear separation between our participant groups, so we initially used the high (25°) and low (5°) values as our criteria. However, through pilot testing, we found it very difficult to locate individuals with 25° of ankle DF-ROM assessed with the knee extended and lowered the cutoff point to 15° for this study. These cutoff points (normal, $\geq$15°; limited, $\leq$5°) allowed us to create groups with distinctly different and nonoverlapping passive-ankle DF-ROM during participant recruitment. In a separate testing session, ankle DF-ROM was assessed using 2 techniques: (1) NWB knee extended and (2) weight-bearing lunge to reclassify participants into normal and limited groups to investigate differences in knee and ankle kinematics during functional tasks. The measurements obtained during the testing session are reported.

Forty physically active participants, 20 men and 20 women, were identified through a larger screening of 67 individuals who volunteered to participate in this research study and met the inclusion criteria. In total, 10 men and 10 women were allocated to both the normal and limited-motion groups.

Participant demographics are depicted in Table 1. All participants were *physically active*, which was defined as 30 minutes of moderate physical activity at least 3 times per week. Volunteers were excluded from this study if they had a NWB, passive-ankle DF-ROM measurement between 6° and 14°; a history of any lower extremity surgical procedure; a history of a lower extremity injury during the previous 6 months that limited their physical activity for

**Table 1. Participant Demographics by Group**[a]

| Characteristic | Assessment | | | |
|---|---|---|---|---|
| | Nonweight-Bearing Position | | Weight-Bearing Lunge | |
| | Normal (n = 20) | Limited (n = 20) | Normal (n = 20) | Limited (n = 20) |
| Ankle-dorsiflexion criteria, ° | ≥15 | ≤5 | ≥44 | ≤43 |
| | Mean ± SD | | | |
| Age, y | 20.70 ± 1.98[b] | 19.45 ± 1.40[b] | 20.70 ± 1.95[b] | 19.45 ± 1.43[b] |
| Height, cm | 172.33 ± 9.73 | 171.12 ± 8.64 | 170.22 ± 9.77 | 173.23 ± 8.34 |
| Mass, kg | 70.13 ± 13.80 | 70.42 ± 12.50 | 67.77 ± 14.10 | 72.78 ± 11.60 |
| Ankle-dorsiflexion range of motion, ° | 16.78 ± 2.16[c] | 1.63 ± 2.58[c] | 50.84 ± 5.16[c] | 38.91 ± 3.48[c] |

[a] Twelve of 40 participants (30%) switched groups (70% remained in the same group).
[b] Group differences, $P < .05$.
[c] Group differences, $P < .001$.

2 or more days; or a known neurologic disorder. Before data collection, each participant read and signed an informed consent document approved by the university's institutional review board (which also approved the study) and completed a general medical history form to verify inclusion criteria.

## Instrumentation

We took NWB ankle DF-ROM measures with a standard, 19-in (0.48-m), plastic goniometer for the screening and again during the testing session.[23] Ankle DF-ROM during the weight-bearing lunge (WBL) was measured using a digital inclinometer (The Saunders Group, Chaska, MN).[22] Knee and ankle kinematics were captured using an electromagnetic motion-tracking system (Motion Star; Ascension Technology Corporation, Milton, VA) at a sampling frequency of 140 Hz. All kinematic and kinetic data were processed using MotionMonitor Software (Innovative Sports Training, Inc, Chicago, IL) and were exported into a customized software program (MATLAB 11; MathWorks, Natick, MA) for data reduction. We used a nonconductive force plate (Bertec Corp, Columbus, OH) to collect kinetic data sampled at 1400 Hz to determine initial contact during the JL task.

## Screening Session

For screening, each potential participant's NWB ankle DF-ROM was assessed for the dominant leg with the participant lying supine on a treatment table (Figure 1). The *dominant leg* was defined as the leg used to kick a ball for maximum distance, and all testing was performed on that extremity. The examiner moved the ankle into plantar flexion and then placed the ankle in a subtalar-neutral position using palpation. He or she passively dorsiflexed the ankle, while maintaining a subtalar-neutral position, until the point of first resistance. At that point, the examiner measured the angle formed by the shaft of the fibula and the lateral midline of the foot using a standard goniometer.[24] That assessment was performed with the subtalar joint in neutral to avoid movement compensations at the subtalar and midtarsal joints and to effectively evaluate talocrural joint motion. The participants who met the inclusion criteria (normal, ≥15°; limited, ≤5°) were asked to schedule a separate testing session.

**Figure 1. Nonweight-bearing ankle-dorsiflexion range-of-motion assessment.**

## Testing Procedures

Once participants were identified and assigned to a group through the initial screening, they reported to the laboratory for a single testing session with the primary researcher (K.E.D.). She recorded height and body mass for each participant, who then completed a 5-minute, upper body, cardiovascular warm-up on a stationary bicycle at moderate intensity as determined by a rate of perceived exertion of 3 of 10. An upper-body warm-up was chosen so that the ROM assessments would not be influenced by pedaling a bicycle with the lower extremities.

Ankle DF-ROM was assessed using both an NWB method and a WBL method performed in randomized order. The NWB ankle DF-ROM method involved the same testing procedure used in the screening session. Three trials were recorded for the dominant leg, and the arithmetic mean was used for data analysis. The measurements recorded during this testing session confirmed group allocation and were used for data analysis; ie, all measurements were taken on the same day.

The weight-bearing method used the WBL test (Figure 2). To perform the WBL, the participant was asked to place the foot perpendicular to the wall with the second toe and midline of the heel placed directly on a piece of guide tape placed on the floor. He or she was then instructed to lunge the knee forward toward the wall until *maximum ankle DF* was reached, which was identified as the heel lifting off the ground. If the knee contacted the wall, the foot was moved posteriorly until the maximum range of DF was achieved. The examiner placed a digital inclinometer distal to the

**Figure 2. Weight-bearing lunge test.**

tibial tuberosity to measure the angle of the tibia relative to vertical with the heel in contact with the ground.[22] The position of the subtalar joint was not controlled during this assessment, which is similar to the way the test is often performed clinically. The examiner took the measurement 3 times on the dominant leg and recorded the arithmetic mean for data analysis. Before testing, we established the intrarater reliability for the investigator performing all measurements (K.E.D.) and demonstrated excellent reliability for the NWB DF-ROM (intraclass correlation coefficient [3,k], 0.988; standard error of measurement, 0.88°) and WBL (intraclass correlation coefficient [3,k], 0.953; standard error of measurement, 1.61°) tests.

After the examiner recorded the ROM measurements, she prepared the participant for motion-analysis data collection. Electromagnetic tracking sensors were placed on the skin with double-sided tape and secured with prewrap and athletic tape. The sensors were placed unilaterally on the dominant leg over the midshaft of the second-third metatarsals of the foot, anteromedial aspect of the proximal tibia, lateral aspect of the thigh, and the spinous process of L5. The shoe was unlaced, and the tongue was pulled forward and fastened to the top of the shoe with double-sided tape to expose the dorsum of the foot and allow sensor placement. The shoe was then relaced up the side, so that no laces crossed over to the opposite side and potentially touched the sensor. The shoelace was tied together once it reached the top of the shoe to ensure proper fit. This procedure was performed as in previous research[25] to allow space for the sensor on the foot and to permit the participant to wear an athletic shoe to perform the double-legged JL. Participants wore their own athletic shoes but did not wear socks so the sensor could be firmly attached to the skin. The shoes were removed for the SLS and OHS by simply untying the top bow and sliding the foot out, without disrupting the sensor placement, to allow for barefoot completion of those 2 tasks. The space gained by removing the tongue of the sneaker was ample for the sensor, which was approximately 8 mm by 20 mm, so that no disruption of the sensor occurred. The sensor data, which indicated the orientation and position of each sensor relative to a standard-range transmitter, were conveyed back to a personal computer. The dominant limb was modeled by digitizing 6 additional landmarks to define the hip-, knee-, and ankle-joint centers. The *knee-joint center* was defined as the midpoint between the digitized medial and lateral femoral condyles, and the *ankle-joint center* was defined as the midpoint between the medial and lateral malleoli. Left and right sides of the anterior-superior iliac spine were digitized to determine the hip-joint center of rotation using the Bell et al[26] method. Global and segment axis systems were established with the x-axis designated as positive in the anterior direction from the participant, the y-axis positive to the left, and the z-axis positive in the upward direction.

Each participant completed OHS, SLS, and JL tasks in a randomized order. The OHS task was performed with the feet shoulder-width apart, arms raised vertically overhead, heels on the ground, and squatting to at least 60° of knee flexion.[7] The SLS was performed with the hands on the hips, opposite leg raised in front of the participant with the foot approximately 10 cm off the ground, squatting to at least 60° of knee flexion.[27] A metronome set at 60 beats/min was used to ensure similar cadences of the squatting task for each participant. The examiner instructed participants to descend as far as possible for 2 beats and to return to the starting position in 2 beats.[27] She ensured that each participant reached at least 60° of knee flexion and returned to the starting position by viewing the knee-flexion curve in the MotionMonitor immediately after each set of squats. The starting position for participants was in the sagittal-plane resting position during double-legged and single-legged stances for the OHS and SLS, respectively. Therefore, some participants were slightly hyperextended, and some were slightly flexed to start. The mean knee-flexion angle in the starting position was 8° for the OHS and 12° for the SLS for both the normal and limited ROM groups. There were no differences between groups for knee-flexion starting angles, regardless of the DF-ROM assessment used for grouping. Not all participants may have returned to exactly 0°, but the examiner ensured they consistently returned to their starting positions because our goal was to capture the natural movement. Squat trials were considered successful if the participant reached at least 60° of knee flexion, returned to the starting position, maintained the hands overhead or on the hips (OHS, SLS), maintained the metronome cadence, and was able to maintain balance during the SLS. Each participant performed 5 consecutive trials of the OHS and SLS; the 3 middle trials were used for data analysis. If necessary, the participant performed additional trials of the task to ensure 3 successful trials were captured.

The JL task consisted of the participant jumping from a 30-cm box placed at a distance of 50% of the standing height away from the force plate, landing on the force plate, and immediately jumping vertically as high as possible. He or she jumped horizontally from the box to the force plate.[9] The examiner orally instructed each participant on how to complete each task and allotted up to 5 practice trials of each task before collecting data. No additional oral instructions were given during the data-collection trials. A JL trial was considered successful if the participant pushed equally off both feet when leaving the box, landed with the dominant foot in the center of the force plate, and did not hesitate before jumping vertically for maximum height. The investigator confirmed those criteria visually. Each participant performed 5 JL trials, and the middle 3 trials were used for data analysis. All participants were able to perform 3 successful trials.

A 1-minute rest period was allotted between the practice trials and data-collection trials. Thirty seconds of rest were provided between trials of a task, and then 1 minute of rest was provided between tasks.

## Data Reduction and Analysis

We estimated 3-dimensional coordinates of the lower extremity bony landmarks using the MotionMonitor software. An embedded, right-handed, Cartesian-coordinate system was defined for the foot, shank, thigh, and pelvis segments to describe the 3-dimensional position and orientation of those segments. All kinematic data were smoothed with a Butterworth fourth-order, zero-phase lag, low-pass digital filter at 14.5 Hz.[9] Kinematic and kinetic data were reduced using custom MATLAB software. We calculated 3-dimensional knee- and ankle-joint angles using a Euler-angle sequence, rotating in an order of (1) flexion-extension (y-axis), (2) valgus-varus (x-axis), and (3) internal-external rotation (z-axis). Data were analyzed during the descent phase of each task. During the squat tasks, the descent phase was operationally defined as the time from initiation of knee-flexion motion until the time of peak knee flexion for each trial. During the JL, the descent phase was operationally defined as the period from the first time the vertical ground-reaction force exceeded 10 N until the time of peak knee flexion. We calculated joint displacements during the descent phase of all tasks for the following motions: knee flexion, knee valgus, knee varus, knee internal rotation, knee external rotation, and ankle DF. Joint-displacement values were calculated as the difference between the peak angle achieved during the descent phase and the starting angle or angle at initial ground contact for the squat tasks and JL, respectively. The joint-displacement values were calculated for each of the middle 3 trials, and the arithmetic mean of those values was used for analyses.

## Statistical Analysis

We conducted separate 1-way analyses of variance, 1 for each task, to analyze differences in knee- and ankle-kinematic displacements and peak values between groups based on the NWB ankle DF-ROM measure (normal, n = 20; limited, n = 20).

The 50th percentile was calculated for the WBL measurements to determine the cutoff point that would categorize all participants into 2 equal groups representing normal and limited ROMs for this population. Separate 1-way analyses of variance, 1 for each task, were performed to analyze differences in knee- and ankle-kinematic displacements and peak values between groups based on the WBL measure (normal, 20; limited, 20). Ankle DF-ROM cutoff points for each group, along with means and standard deviations, are depicted in Table 1. Most participants (70%; 28 of 40) remained in the same group (normal or limited) for both ankle DF-ROM assessments. Six of the 40 participants (15%) were limited on NWB but normal on WBL, whereas 6 other participants (15%) were normal on NWB but limited on WBL.

We set the a priori $\alpha$ level at $P = .05$ for all analyses. All statistical analyses were performed using SPSS (version 19.0; SPSS Inc, Chicago, IL).

## RESULTS

No significant differences were observed between the NWB DF-ROM groups before data collection in average height ($P = .68$) or body mass ($P = .95$). The groups were different in age (normal, 21 ± 2 years; limited, 20 ± 1 years; $P = .03$); however, the mean difference in age was 1.25 years. Similarly, no height ($P = .30$) or body mass ($P = .23$) differences were evident when we grouped participants based on the WBL test. Means and standard deviations for participant demographics for both group classifications are reported in Table 1.

### The NWB Ankle DF-ROM Group Classification

We observed no significant differences between the normal and limited groups during the OHS (Table 2), SLS (Table 3), or JL tasks (Table 4) for any joint-displacement variable when participants were classified based on the NWB ankle DF-ROM measure with the knee extended. No significant differences were noted for peak joint angles.

### The WBL Ankle DF-ROM Group Classification

Means, standard deviations, 95% confidence intervals, and effect sizes for all joint-displacement variables during the OHS, SLS, and JL tasks are reported in Tables 2 through 4, respectively. During the OHS (Table 2), the normal group (WBL $\geq$ 44.02°) displayed greater knee-flexion displacement (mean difference, 14.94°; $F_{1,39} = 12.65$; $P = .001$) and greater ankle DF displacement (mean difference, 7.89°; $F_{1,39} = 21.21$; $P < .001$) compared with the limited group (WBL $\leq$ 44.01°). During the SLS (Table 3), the normal group demonstrated greater knee-flexion displacement (mean difference, 12.39°; $F_{1,39} = 13.19$; $P = .001$), greater ankle DF displacement (mean difference = 6.44°; $F_{1,39} = 15.88$; $P < .001$), and greater knee-varus displacement (mean difference, 5.50°; $F_{1,39} = 4.16$; $P = .048$;) than the limited group.

Additionally, the normal group demonstrated greater peak knee flexion during the OHS (normal, 112.71° ± 13.48°; limited, 97.45° ± 14.34°; mean difference, 15.26°; $F_{1,39} = 12.02$; $P = .001$) and SLS (normal, 88.71° ± 12.73°; limited, 77.09° ± 10.20°; mean difference, 11.62°; $F_{1,39} = 10.15$; $P = .003$) in comparison with the limited group. We observed no group differences between knee-flexion angles at the starting position for the OHS (normal, 8.04° ± 7.84°; limited, 8.57° ± 5.22°; mean difference, 0.53°; $F_{1,39} = 0.07$; $P = .800$) or SLS (normal, 12.35° ± 6.35°; limited, 13.12° ± 4.47°; mean difference, 0.77°; $F_{1,39} = 0.20$; $P = .660$). No group differences were noted during the JL tasks (Table 4).

## DISCUSSION

Our most important finding was that individuals with limited ankle DF-ROM during the WBL demonstrated altered knee- and ankle-joint kinematics. Specifically, those with limited ankle DF-ROM during the WBL displayed less knee-flexion and ankle-DF displacement during the squatting tasks. In addition, those same individuals showed

Table 2. Overhead-Squat Lower Extremity Kinematics for Groups Based on the Nonweight-Bearing–Position and Weight-Bearing–Lunge Assessments

| | Ankle-Dorsiflexion Range of Motion | | | | | |
|---|---|---|---|---|---|---|
| | Nonweight-Bearing Position | | | Weight-Bearing Lunge | | |
| | Mean ± SD (95% Confidence Interval) | | | Mean ± SD (95% Confidence Interval) | | |
| Displacement$^a$ | Normal (n = 20) | Limited (n = 20) | Effect Size | Normal (n = 20) | Limited (n = 20) | Effect Size |
| Knee flexion | 100.38 ± 13.73 (93.68, 107.08) | 92.56 ± 15.79 (85.87, 99.26) | 0.53 | 103.94 ± 11.79$^b$ (98.42, 109.46) | 89.00 ± 14.62$^b$ (82.16, 95.85) | 1.31 |
| Knee valgus | −2.36 ± 3.86 (−3.72, −1.00) | −1.29 ± 1.72 (2.65, 0.07) | 0.38 | −1.72 ± 3.60 (−3.40, −0.03) | −1.93 ± 2.37 (−3.04, −0.82) | 0.07 |
| Knee varus | 13.41 ± 10.47 (7.95, 18.87) | 17.14 ± 13.48 (11.68, 22.61) | 0.31 | 15.47 ± 9.09 (11.22, 19.73) | 15.08 ± 14.69 (8.20, 21.96) | 0.03 |
| Knee external rotation | −5.59 ± 7.82 (−8.38, −2.81) | −3.60 ± 3.80 (−6.38, −0.81) | 0.34 | −4.66 ± 7.82 (−8.32, −1.00) | −4.52 ± 4.07 (−6.43, −2.62) | 0.02 |
| Knee internal rotation | 14.87 ± 14.92 (8.63, 21.11) | 11.11 ± 12.56 (4.87, 17.36) | 0.27 | 16.17 ± 13.03 (10.07, 22.27) | 9.82 ± 14.02 (3.25, 16.38) | 0.47 |
| Ankle dorsiflexion | −30.03 ± 7.45 (−32.96, −27.11) | −26.14 ± 5.28 (−29.06, −23.21) | 0.61 | −32.03 ± 6.36$^b$ (−35.01, −29.05) | −24.14 ± 4.27$^b$ (−26.14, −22.15) | 1.49 |

[a] Kinematic sign convention: +, knee flexion, knee varus, and knee internal rotation; −, knee valgus, knee external rotation, and ankle dorsiflexion.

[b] Group differences, $P \leq .001$.

Table 3. Single-Legged Squat Lower Extremity Kinematics for Groups Based on the Nonweight-Bearing–Position and Weight-Bearing–Lunge Assessments

| | Ankle-Dorsiflexion Range of Motion | | | | | |
|---|---|---|---|---|---|---|
| | Nonweight-Bearing Position | | | Weight-Bearing Lunge | | |
| | Mean ± SD (95% Confidence Interval) | | | Mean ± SD (95% Confidence Interval) | | |
| Displacement$^a$ | Normal (n = 20) | Limited (n = 20) | Effect Size | Normal (n = 20) | Limited (n = 20) | Effect Size |
| Knee flexion | 75.58 ± 11.00 (67.02, 78.13) | 67.74 ± 13.42 (62.20, 73.30) | 0.64 | 76.36 ± 11.02$^b$ (71.20, 81.52) | 63.97 ±10.55$^b$ (57.07, 67.64) | 1.51 |
| Knee valgus | −2.44 ± 2.74 (−3.38, −1.50) | −1.15 ± 1.08 (−2.10, −0.21) | 0.67 | −1.83 ± 2.23 (−2.87, −0.78) | −1.77 ± 2.14 (−2.76, −0.77) | 0.03 |
| Knee varus | 11.25 ± 10.96 (7.19, 15.32) | 10.45 ± 6.40 (6.39, 14.52) | 0.09 | 13.60 ± 10.28$^c$ (8.80, 18.41) | 8.10 ± 6.32$^c$ (5.14, 11.06) | 0.66 |
| Knee external rotation | −6.36 ± 5.46 (−8.74, −3.97) | −5.32 ± 5.07 (−7.71, −2.94) | 0.20 | −4.79 ± 3.96 (−6.64, −2.94) | −6.89 ± 6.18 (−9.78, −3.40) | 0.41 |
| Knee internal rotation | 5.90 ± 5.38 (3.84, 7.95) | 4.04 ± 3.51 (1.98, 6.09) | 0.42 | 6.30 ± 5.16 (3.89, 8.72) | 3.63 ± 3.56 (1.97, 5.30) | 0.61 |
| Ankle dorsiflexion | −29.02 ± 5.84 (−31.68, −26.36) | −25.89 ± 5.90 (−28.54, −23.23) | 0.53 | −30.67 ± 5.67$^b$ (−33.33, −28.02) | −24.23 ± 4.49$^b$ (−26.33, −22.13) | 1.86 |

[a] Kinematic sign convention: +, knee flexion, knee varus, and knee internal rotation; −, knee valgus, knee external rotation, and ankle dorsiflexion.

[b] Group differences, $P \leq .001$.

[c] Group differences, $P < .05$.

greater knee-varus displacement during the SLS. However, we found no differences in knee and ankle displacement between normal and limited groups when classifying groups based on NWB ankle DF-ROM measures. Generally, these results support our hypothesis that restricted ankle DF-ROM results in altered lower extremity movement patterns during functional tasks, such as squatting; however, this does not appear to be the case for JL tasks. The method used to assess ankle DF-ROM influenced the study's results as group differences in knee and ankle kinematics during squatting were only present when identifying participants as limited based on WBL ankle DF-ROM measurements.

Nonweight-bearing ankle DF-ROM measures have been shown to influence lower extremity kinematics during functional tasks. Thus, we were surprised to see no differences in lower extremity kinematics between normal and limited groups when classifying participants using the NWB ankle DF-ROM method. Fong et al[19] observed greater NWB ankle DF-ROM (assessed with the knee straight) associated with greater knee flexion during a JL task. Differences in the JL task performed may explain the contrasting results between studies. In our study, participants performed a landing from a 30-cm box followed by an immediate countermovement jump for maximal height. The participants in the research by Fong et al[19] also performed a similar landing from a box, but they did not incorporate a maximal vertical jump. Incorporating the countermovement jump after the box landing may have limited the amount of ankle-DF displacement after impacting the ground because participants were attempting to immediately recoil and jump for maximal vertical height, thus limiting our ability to detect group differences. In addition, Fong et al[19] studied healthy, physically active individuals with no known ROM restrictions and reported 14.3° ± 5.5° of DF-ROM assessed with the knee extended. In the current study, we intentionally recruited individuals with known restrictions as well as individuals with normal ROM. Our values for the same assessment were much smaller for our limited group (1.63° ± 2.58°) and larger for our normal group (16.78° ± 2.16°). Those differences in sample populations could certainly have contributed to differences in the study results.

It is not clear why we did not see differences in lower extremity kinematics during the squatting tasks when classifying participants based on NWB ankle DF-ROM measures. Bell et al[7] reported decreased NWB ankle DF-ROM in those who displayed medial knee displacement (knee-valgus collapse) during a double-legged squat compared with those who did not. Mauntel et al[27] observed similar findings in those who demonstrated medial knee displacement during an SLS task. The NWB ankle DF-ROM measure and squat tasks we used were nearly identical to those reported by Bell et al[7] and Mauntel et al.[27] However, these previous authors based group assignment on the visual observation of medial knee displacement, whereas we classified groups based on NWB ankle DF-ROM. This suggests that the visual observation of medial knee displacement is associated with limited NWB ankle DF-ROM; yet, limited ankle DF-ROM does not necessarily result in altered movement patterns at the knee, such as medial knee displacement.

**Table 4. Jump-Landing Lower Extremity Kinematics for Groups Based on the Nonweight-Bearing–Position and Weight-Bearing–Lunge Assessments**

| | Ankle-Dorsiflexion Range of Motion | | | | | |
|---|---|---|---|---|---|---|
| | Nonweight-Bearing Position | | | Weight-Bearing Lunge | | |
| | Mean ± SD (95% Confidence Interval) | | | Mean ± SD (95% Confidence Interval) | | |
| Displacement[a] | Normal (n = 20) | Limited (n = 20) | Effect Size | Normal (n = 20) | Limited (n = 20) | Effect Size |
| Knee flexion | 76.14 ± 14.72 (69.59, 82.70) | 74.38 ± 14.23 (67.83, 80.93) | 0.12 | 75.34 ± 14.84 (68.40, 82.29) | 75.18 ± 14.16 (68.55, 81.81) | 0.01 |
| Knee valgus | −1.54 ± 2.48 (−2.45, −0.64) | −0.77 ± 1.37 (−1.68, 0.14) | 0.4 | −0.73 ± 1.14 (−1.26, 0.20) | −1.58 ± 2.58 (−2.80, −0.37) | 0.46 |
| Knee varus | 11.80 ± 8.87 (8.18, 15.43) | 12.99 ± 7.03 (9.36, 16.62) | 0.15 | 11.14 ± 7.41 (7.67, 14.61) | 13.65 ± 8.42 (9.71, 17.59) | 0.32 |
| Knee external rotation | −3.78 ± 5.03 (−5.74, −1.81) | −1.79 ± 3.51 (−3.75, 0.18) | 0.47 | −2.26 ± 4.35 (−4.30, −0.23) | −3.30 ± 4.50 (−5.41, −1.20) | 0.24 |
| Knee internal rotation | 15.70 ± 15.83 (9.75, 21.65) | 12.12 ± 9.76 (6.17, 18.07) | 0.28 | 16.82 ± 14.49 (10.03, 23.60) | 11.00 ± 11.18 (5.77, 16.23) | 0.45 |
| Ankle dorsiflexion | −52.02 ± 19.11 (−60.03, −44.02) | −52.71 ± 16.14 (−60.72, −44.71) | 0.04 | −50.24 ± 19.63 (−59.42, −41.05) | −54.50 ± 15.20 (−61.62, −47.39) | 0.24 |

[a] Kinematic sign convention: +, knee flexion, knee varus, and knee internal rotation; −, knee valgus, knee external rotation, and ankle dorsiflexion.

It is possible that other neuromuscular alterations, in addition to limited NWB ankle DF-ROM, are present in individuals with altered lower extremity movement patterns. Padua et al[28] recently evaluated the neuromuscular characteristics of the lower extremity muscles in the same participants who demonstrated medial knee displacement during the double-legged squat, which was eliminated with a 2-in (5.08-cm) heel lift.[7] The medial-knee–displacement group displayed significantly greater muscle activation of the hip adductor, gastrocnemius, and tibialis anterior muscles in comparison with the control group. The heel lift not only eliminated medial knee displacement but also decreased muscle activation during the descent phase of the squat in the gastrocnemius and tibialis anterior muscles by 32% and 55%, respectively. In a population displaying medial knee displacement, increasing the tibial angle in the anterior direction with a heel lift was successful in improving knee mechanics. However, hip-adductor muscle activation, which contributes to medial knee displacement, was not altered with the heel lift. Knee kinematics are affected by both proximal and distal influences. Our participants had restricted ankle DF-ROM but not necessarily medial knee displacement. Therefore, it is likely the neuromuscular characteristics were different in the sample populations. The combination of altered muscle activation[27,28] and limited NWB ankle DF-ROM[7,27] may be necessary to ultimately facilitate altered lower extremity kinematics.

Limited ankle DF during movement may facilitate compensations at the foot and ankle joints but may not affect the knee in some individuals. The participants in our study had limited ankle DF but no history of lower extremity surgery and no musculoskeletal injury in the previous 6 months. Limited motion in healthy, physically active individuals can be due to a variety of factors, including soft tissue tightness (gastrocnemius, soleus, Achilles tendon), osteokinematic restrictions of the bones and joints (flexion-extension), arthrokinematic restrictions (roll, glide, spin), or even frequently wearing high-heeled shoes, among others. Previous researchers[29,30] have suggested that limited ankle DF contributes to excessive rearfoot pronation, calcaneal eversion, and talar-head adduction and plantar flexion. Essentially, because of limited sagittal-plane motion, the foot moves more in the frontal plane to achieve stability and successful movement. Talar-head movement during pronation may cause internal rotation of the tibia and medial displacement at the knee. However, it is possible that not all individuals with ankle DF-ROM restrictions compensate in that manner. We did not quantify foot kinematics, so we can only speculate.

In contrast to NWB measures, ankle DF-ROM assessed during the WBL differentiated lower extremity kinematics between the normal and limited groups. Individuals whose WBL ankle DF-ROM was limited displayed less sagittal-plane displacement at the knee and ankle during the squatting tasks as well as smaller peak knee-flexion angles. We consider those differences in knee and ankle displacements to be large and clinically meaningful because the associated effect sizes ranged from 1.31 to 1.86 (Tables 2 and 3). Our findings are consistent with those of Macrum et al,[13] who noted that altering the ankle DF starting position resulted in reduced knee-flexion displacement during a double-legged squat. Macrum et al[13] placed a 12° wedge under the participant's forefoot to position the ankle in greater DF and ultimately reduce the available amount of DF motion (restricted ankle DF) during a double-legged squat task. That resulted in decreased peak knee flexion and overall knee-flexion displacement compared with performing the double-legged squat without a forefoot wedge in place (ie, unrestricted ankle DF). Additionally, Hoch and McKeon[31] reported that the WBL ankle DF-ROM predicted anterior-reach distance during the Star Excursion Balance Test ($R^2 = 0.28$). Single-legged squat depth, which is largely influenced by knee-flexion displacement, is a key factor contributing to the anterior-reach distance during the Star Excursion Balance Test. Thus, these combined findings demonstrate the importance of WBL ankle DF-ROM as a factor influencing knee-flexion displacement.

Frontal-plane knee motion was also different in those with limited ankle DF-ROM during the WBL. Specifically, those with greater ankle DF-ROM during the WBL demonstrated increased knee-varus displacement during the SLS. This observation is in agreement with the results of Sigward et al,[14] who reported a significant association between greater frontal-plane knee valgus motion and lesser DF-ROM.

These findings may provide insight for ACL injury and injury-prevention strategies given the alterations in sagittal-plane displacements (decreased knee flexion) in those with limited ankle DF-ROM during the WBL and frontal-plane knee motion (increased knee varus) in those with greater DF-ROM during the WBL. Video analyses have repeatedly shown the body to be in an erect posture (decreased knee flexion) when noncontact ACL injuries occur.[32,33] Decreased knee flexion may also be important, given how it influences ACL loading: less knee flexion results in a larger patellar tendon–tibial shaft angle, thus producing greater anterior tibial shear force during quadriceps contraction.[34,35] In addition, the ability of the hamstrings to offset anterior tibial shear forces and reduce ACL loading is reduced in positions of less knee flexion.[35] Increased knee-valgus motion and loading are also associated with a higher risk of ACL injury and are observed during ACL injury mechanisms.[33,36,37] Individuals with greater ankle DF-ROM during the WBL did not demonstrate knee-valgus motion but, rather, displayed greater knee-varus displacement than those with limited ankle DF-ROM during the WBL. Thus, interventions aimed at increasing ankle DF-ROM during the WBL may facilitate increased knee-flexion and -varus displacements and help minimize anterior shear force and knee-valgus–related ACL loading, respectively.

## Limitations

Previous researchers have shown that participants who demonstrate medial knee displacement during an OHS[7] and medial knee excursion during a drop landing[14] also have less ankle DF ROM assessed in NWB with 30° of knee flexion. One potential limitation of our study is that we evaluated and categorized individuals based on an NWB assessment with the knee in full extension. However, we also measured ankle DF-ROM with the knee flexed during our data-collection session (normal, 22.27° ± 4.49°; limited, 8.52° ± 3.76°). We performed a Pearson product moment correlation coefficient analysis among the 3 assessments (knee flexed, knee extended, WBL) and found a strong association between both NWB measures ($r = 0.919$; $P < .001$). This indicates that our kinematic results would have been similar had we grouped participants based on an NWB measure with the knee flexed. We also calculated the 50th percentile cutoff point (16°) in the same manner as we did for the WBL test and noted similar group means (normal, 22.30 ± 4.45; limited, 8.48 ± 3.69). One participant switched from the limited group to the normal group, and 1 participant switched from the normal group to the limited group. Therefore, we feel confident that the kinematic data would be the same as our current results regardless of grouping participants using the NWB measure with the knee extended or flexed.

Inherent differences exist in the measurement techniques for the 2 DF-ROM assessments used in this study. Often, when clinicians measure ankle DF-ROM in an NWB position, they maintain the subtalar joint in neutral position to confirm they are measuring true DF at the talocrural joint. However, the WBL is typically performed efficiently in the clinic without controlling subtalar position. The potential benefit of this assessment is that it better evaluates functional movement of the entire foot and ankle complex. We do not control for subtalar-joint position during movement-screening sessions using the OHS, SLS, and JL, so we felt comfortable performing the WBL assessment in this manner. The amounts of available motion during these 2 assessments are very different, with greater motion achieved when subtalar position is not controlled. Although this may be a potential limitation of this study, we did not directly compare the 2 measures; therefore, we do not feel this is a limitation of our findings.

Peak joint angles were identified during the descent phase of each task. However, we do know when, during the descent phase of each task, the peak angle occurred. We are unsure whether the peak knee-flexion angle occurred simultaneously with the peak ankle-DF angle. The various timings of peak angles may have an influence on injury.

Finally, we were not blinded to the participants' group assignment, which may have caused unintentional bias during ROM measurements. Yet the measurement techniques were standardized with good reliability. Our results are generalizable only to healthy, college-aged individuals. Therefore, whether results would be similar in an injured population is unclear. Additionally, we did not assess muscle activation or muscle strength as variables in this study, but it would be beneficial to investigate them in the future.

### Recommendations for Future Research

Future researchers should continue to investigate the influence of ankle DF-ROM on lower extremity kinematics. Intervention studies would be beneficial to determine whether altering ankle DF ROM, through addressing soft tissue or arthrokinematic restrictions, results in altered lower extremity kinematics in a way that is beneficial for rehabilitation and injury prevention.

## CONCLUSIONS

Our results suggest that ankle DF-ROM during the WBL may be a more sensitive measure for identifying those at risk for high-risk movement patterns compared with NWB passive-ankle DF-ROM measures. Ankle DF-ROM is reported to be restricted in physically active individuals and after lower extremity injury; however, those measurements typically use passive NWB measurements.[38] Although those passive measurements remain important, our findings suggest that including the WBL in the assessment of ankle DF-ROM is also important and may better identify those at risk for dysfunctional movement patterns during functional tasks.

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