Modulation of Frontal-Plane Knee Kinematics by Hip-Extensor Strength and Gluteus Maximus Recruitment During a Jump-Landing Task in Healthy Women

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**Context:** Abnormal lower extremity kinematics during dynamic activities may be influenced by impaired gluteus maximus function. **Objective:** To examine whether hip-extensor strength and gluteus maximus recruitment are associated with dynamic frontal-plane knee motion during a jump-landing task. **Design:** Exploratory study. **Setting:** Biomechanics laboratory. **Participants:** 40 healthy female volunteers. **Main Outcome Measures:** Isometric hip-extension strength was measured bilaterally with a handheld dynamometer. Three-dimensional hip and knee kinematics and gluteus maximus electromyography data were collected bilaterally during a jump-landing test. Data were analyzed with hierarchical linear regression and partial correlation coefficients (α = 0.05). **Results:** Hip motion in the transverse plane was highly correlated with knee motion in the frontal plane (partial r = .724). After controlling for hip motion, reduced magnitudes of isometric hip-extensor strength (partial r = .470) and peak gluteus maximus recruitment (partial r = .277) were correlated with increased magnitudes of knee valgus during the jump-landing task. **Conclusion:** Hip-extensor strength and gluteus maximus recruitment, which represents a measure of the muscle’s neuromuscular control, are both associated with frontal-plane knee motions during a dynamic weight-bearing task.

**Keywords:** biomechanics, electromyography, muscle function, knee joint

Women are at higher risk of noncontact knee injuries than are men.1,2 While reasons for that elevated risk are likely multifactorial, diminished hip muscle strength and altered lower extremity kinematics have been implicated as risk factors.3–5 Impaired hip muscle strength may lead to excessive hip adduction and medial rotation during weight-bearing activities,3,6–10 which can lead to a concomitant increase in knee valgus that is theorized to cause knee injury.5,11,12

Impaired neuromuscular control at the hip may also contribute to the excessive knee valgus that induces knee injuries. Neuromuscular control, operationally defined as preparatory or reactionary but unconscious muscle activation in response to joint movements and loading conditions for the purpose of maintaining functional joint stability,13 is reflected by electromyogram (EMG) signals that display the neural input that drives muscle contractions. As an example, women land from jumps with less gluteus maximus recruitment than do men, and the magnitude of gluteus maximus recruitment during unilateral step-downs correlates negatively with knee valgus.14,15 Given the anatomical orientation of the gluteus maximus, this relationship may make sense since the gluteus maximus is aligned and leveraged to extend, laterally rotate, and assist in abduction of the hip. Recruiting the gluteus maximus during weight-bearing activities may limit excessive medial hip rotation or hip adduction, thereby limiting knee valgus motions. This inference implies that altered neuromuscular control at the hip may influence knee kinematics.

Few studies have examined the extent to which gluteus maximus strength and neuromuscular control uniquely contribute to frontal-plane knee kinematics. Hollman et al16 showed that increased gluteus maximus recruitment can compensate for impaired hip-extension strength and mitigate kinematic changes at the knee during a jump-landing task but did not report the unique contributions of variance in muscle strength or recruitment to variance in the kinematic performance of the motor task. The purpose of this study, therefore, was to quantify the contributions of hip-extensor strength and gluteus maximus recruitment to dynamic frontal-plane knee motion during a jump-landing task in women. We hypothesized that lower magnitudes of isometric hip-extensor strength and lower magnitudes of gluteus maximus recruitment during a jump-landing task would be associated with increased knee valgus. Gaining a better understanding of how gluteus maximus function is associated with knee valgus may facilitate interventions intended to prevent knee injury or to enhance rehabilitation after a knee injury.
Methods

Design
This was an exploratory study in which the associations among 3-dimensional knee kinematics, hip kinematics, hip-extension strength, and gluteus maximus recruitment were examined during a jump-landing task. The dependent variable was the frontal-plane knee angle at maximum knee flexion during the jump-landing cycle, and the independent variables included hip angles in the frontal, sagittal, and transverse planes of motion; isometric hip-extension strength; and peak gluteus maximus recruitment.

Participants
Active, healthy women age 18 to 36 who reported the absence of knee pain while descending stairs, squatting, or during prolonged sitting; who could ambulate without assistive devices; and who could jump and land without difficulty were eligible to participate. Exclusion criteria included reports of musculoskeletal, neuromuscular, cardiopulmonary, or integumentary pathology that impaired motor function; any reported history of knee injury or surgery; and one or more positive tests among the Lachman, posterior drawer, valgus, and varus stress tests for ligamentous stability or joint-line tenderness with palpation indicative of meniscal pathology.

The study was powered to account for 20% or more of the variance in knee valgus angles from among 5 predictor variables including isometric hip strength, gluteus maximus recruitment during a jump-landing task, and triplanar hip angles during the task. Forty participants having both lower extremities tested provided a statistical power (1 – β) that exceeded .90 at α = .05 to detect a cumulative R² value of .20 or higher; therefore, volunteers were screened until 40 met the criteria for participation. All participants provided written informed consent. The study protocol was reviewed and approved by our institutional review board in the spirit of the Declaration of Helsinki.

Instrumentation
To facilitate our understanding of participants’ activity levels, each participant completed a 7-question short form of the International Physical Activity Questionnaire (IPAQ). Muscle strength was measured with a MicroFET 2 dynamometer (Hoggan Health Industries, Inc, West Jordan, UT), and EMG data were measured with Bagnoli DE-3.1 double-differential bipolar surface electrodes and a Bagnoli-16 amplifier (Delsys Inc, Boston, MA). The electrodes were constructed of 99.9% pure silver bars 10 mm in length and 1 mm in width, spaced 10 mm apart and encased within polycarbonate preamplifier assemblies measuring 41 × 20 × 5 mm. The preamplifiers had a gain of 10 V/V, and the system permitted overall amplification from 100 to 10,000 V/V. The common-mode rejection ratio was 92 dB at 60 Hz, input impedance exceeded 10¹⁵ Ω, and estimated noise was ≤1.2 µV. Data were collected at 1000 Hz through a 16-bit NI-DAQ PCI-6220 analog-to-digital acquisition card (National Instruments Corp, Austin, TX). EMG signals were processed with EMGworks 3.7.2.0 data-acquisition and -analysis software. Three-dimensional kinematic data were collected at 100 Hz with a Vicon MX motion-analysis system and 5 high-resolution MX20+ infrared digital cameras (Vicon Motion Systems, Oxford, UK). Vicon Nexus software was used to quantify pelvis and lower extremity kinematics.

Procedures
One of the investigators, a certified athletic trainer, screened participants for eligibility. After eligibility was determined, participants completed the IPAQ and then were prepared for the isometric hip-extensor strength and jump-landing testing procedures. Muscle strength was operationally defined as maximum isometric force-production capability. Hip-extensor strength was tested in a standardized muscle-testing position for the gluteus maximus. Each participant lay in the prone position on a plinth, flexed the knee to approximately 90°, then extended the hip, contracting maximally for approximately 5 seconds against the handheld dynamometer positioned at the distal thigh and stabilized by a strapping belt and an examiner’s hand. The maximum force produced from 3 trials was expressed as a percentage of participants’ body weight (% BW) and used in subsequent analyses. Gluteus maximus recruitment was acquired with the EMG system during the maximum-strength test to establish the amplitude of EMG signals in a maximal contraction to which subsequent data were normalized; EMG signals acquired during the tests were therefore expressed as a percentage of the maximum voluntary isometric contraction (% MVC). Before EMG activity was collected, each participant’s skin was cleansed with alcohol and electrodes were placed over the gluteus maximus, oriented with the muscle’s line of action at approximately one-half of the distance between the sacrum and greater trochanter of the femur. The reference electrode was placed at the left medial malleolus.

After strength testing was completed, 16 retroreflective markers were placed on anatomic landmarks in accordance with Vicon’s Plug-in-Gait marker set to generate the model from which kinematic data were obtained (bilateral posterosuperior iliac spines, lateral aspect and lateral condyles of the thighs, lateral aspect and lateral malleoli of the shanks, and at the posterior aspect of the calcanei and dorsum of the second metatarsophalangeal joint at the feet). After the capture of a neutral standing trial, participants performed a series of 3 consecutive maximum vertical jumps, without rest between the jumps, during which kinematic and EMG data were measured. One practice trial of 3 consecutive jumps was permitted to orient participants to the task. The practice trial occurred before attachment of the retroreflective markers, so sufficient time was allotted between the practice series and...
tested series of jumps to ensure that fatigue would not affect participants’ performance. Data from both limbs were collected and used in subsequent analyses.

Data Processing
Kinematic and EMG data obtained during the jumping tests were processed using standard methods. Local coordinate systems for the pelvis, thighs, shanks, and feet were derived from the neutral standing trial. Marker displacement trajectories were processed with a Woltring quintic-spline filter at a mean square error of 20 mm. Hip- and knee-joint angles were calculated with 3-dimensional Cardan angles whereby rotations about the orthogonal local axes corresponded to flexion (positive angle) and extension (negative angle) in the sagittal plane, hip adduction (positive angle) and abduction (negative angle) and knee varus (positive angle) and valgus (negative angle) in the frontal plane, and medial rotation (positive angle) and lateral rotation (negative angle) in the transverse plane of motion. EMG signals were band-pass filtered between 20 and 450 Hz with a fourth-order Butterworth filter and subsequently processed through a root-mean-square algorithm with 125-millisecond time constants and sliding windows with 50% overlap between successive windows. EMG data collected during the jump-landing tests were normalized to the MVIC and therefore expressed as %MVIC. Peak values of EMG recruitment data were used in subsequent analyses.

Statistical Analysis
Kinematic and EMG data were analyzed during the weight-acceptance (eccentric) phase of the jump-landing cycles, identified from initial contact through the point at which maximum knee flexion was reached. Initial contact was identified in the playback mode of Vicon’s Nexus software as the instant when participants’ dorsal metatarsophalangeal-joint markers stopped descending during the jump-landing cycle. Data from the second of the 3 consecutive jumps specifically were analyzed. The second jump represented a transitional movement after the first jump, the initial movement task, and preceding the third jump, a terminal movement task. Participants’ first jumps typically were performed with lower vertical jump heights than their second and third jumps, which represented more conservative performance. Landing mechanics during the first jump therefore were not representative of mechanics during the second and third jumps. Similarly, mechanics during participants’ third jumps also differed from those during the second jump-landing cycle. When participants completed the third jump—when they were not transitioning to another immediate jump—they landed with less hip and knee flexion, that is, with a stiffer response. Data from the second jump-landing cycle only were therefore included in the analysis. Hip and knee angles were analyzed at the point of maximum knee flexion during the jump-landing cycle.

Descriptive data (means and SDs) were calculated, and hierarchical multiple regression (α = .05) was used to examine the relationship among the dependent variable—frontal-plane knee angle—and the independent variables including hip angles in the sagittal, frontal, and transverse planes of motion; isometric hip-extension strength; and gluteus maximus recruitment. Isometric hip strength and gluteus maximus recruitment were entered hierarchically into the regression model after the hip kinematic data to examine their contributions to frontal-plane knee motion, above and beyond that accounted for by hip kinematics. Partial correlation coefficients were used to examine the unique relationship between each predictor variable and frontal-plane knee motion, controlling for the other variables in the analysis. IBM SPSS 21.0 software was used for all data analyses (IBM Corp, Armonk, NY).

Results
All 40 participants who met criteria for enrollment completed testing. They had normal body-mass indices (mean height = 1.65 ± 0.06 m, mean body mass = 63.1 ± 8.5 kg, mean BMI = 23.2 ± 2.8 kg/m²) and were classified as participating in moderate (n = 23) to high (n = 17) levels of physical activity (<600 MET-minutes per week = low physical activity, 600–3000 MET-minutes per week = moderate physical activity levels, >3000 MET-minutes per week = high physical activity levels). BMI and IPAQ scores were not correlated with frontal-plane knee valgus (r < .01, P = .99, and r = .09, P = .41, respectively).

Participants performed the jump-landing task with approximately 3.0° ± 10.7° of knee valgus (Table 1). In support of our hypothesis, variance in the predictor variables accounted for 60.3% of the variance in frontal-plane knee motion (Table 2; cumulative R² = .60, F5,79 = 22.48, P < .01). Hip angles accounted for 47.8% of the variance (R² = .48, F3,76 = 23.24, P < .01), hip-extension strength accounted for 9.2% of the variance (AR² = .09, F1,75 = 15.99, P < .01), and gluteus maximus recruitment during the jump-landing task accounted for an additional 3.3% of the variance in frontal-plane knee angles (ΔR² = .03.

Table 1 Descriptive Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee angles (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>frontal plane</td>
<td>-3.0</td>
</tr>
<tr>
<td></td>
<td>sagittal plane</td>
<td>56.0</td>
</tr>
<tr>
<td></td>
<td>transverse plane</td>
<td>5.3</td>
</tr>
<tr>
<td>Hip angles (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>frontal plane</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>sagittal plane</td>
<td>57.6</td>
</tr>
<tr>
<td></td>
<td>transverse plane</td>
<td>7.3</td>
</tr>
<tr>
<td>Hip-extension strength (% body weight)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gluteus maximus recruitment (% MVIC)</td>
<td>43.6</td>
</tr>
</tbody>
</table>

Note: Angles in the frontal plane are designated as varus/adduction (positive) and valgus/adduction (negative); in the sagittal plane as flexion (positive) and extension (negative); and in the transverse plane as medial rotation (positive) and lateral rotation (negative).
in strength of the gluteus maximus, assuming that external fixation represents a valid proxy for the force production measured with a handheld dynamometer (Figure 1B and 1C). Assuming that isometric hip-extensor strength and with reduced gluteus maximus recruitment in knee valgus was associated with reduced hip-extension motion, when hip motion was held constant an increase in frontal-plane knee motion. While transverse-plane hip and neuromuscular control would be associated with frontal-plane knee motion during the jump-landing task represents an element of neuromuscular control, the findings support the hypothesis that gluteus maximus strength and neuromuscular control of the gluteus maximus influence frontal-plane knee motion.

The theoretical framework supporting this study is that muscle strength and neuromuscular control are 2 related—but different—elements of physiologic function that contribute to one’s performance during a dynamic motor task. The motor task was a jump-landing task, and performance was represented by the lower extremity kinematics displayed during the task. We sought to understand the extent to which hip-extensor strength and gluteus maximus recruitment uniquely contribute to frontal-plane kinematics during the task. The question is relevant because, while many investigators have reported strength deficits among individuals with lower extremity injuries or who perform functional weight-bearing movements with increased knee valgus, it is evident that strengthening alone is insufficient to induce changes in frontal-plane knee kinematics that may reduce the incidence of knee injuries or enhance rehabilitation after an injury. Neuromuscular control provides insight into how individuals perform motor tasks like landing from a jump or single-limb step-downs. The extent to which one’s muscle strength versus one’s ability to recruit a muscle during the task and the extent to which those elements of physiologic function affect performance are not clear.

The finding that transverse-plane hip motion and hip-extensor strength are associated with frontal-plane knee kinematics during a jump-landing task is consistent with the work of Ireland et al and Niemuth et al, who postulated that excessive medial hip rotation secondary to insufficient hip muscle strength might produce the excessive knee valgus movements that lead to knee injury. While the gluteus maximus is primarily a hip extensor, the muscle also laterally rotates the femur, and therefore its action may limit the excessive medial hip rotation that contributes to increased knee valgus. Moreover, the finding that gluteus maximus neuromuscular control correlates with frontal-plane knee kinematics is consistent with previous research suggesting that reduced levels of gluteus maximus recruitment may be associated with excessive knee valgus. The findings provide support for programs that emphasize neuromuscular-coordination exercises rather than merely muscle-strengthening exercises in knee-injury prevention. While hip-strengthening programs produce stronger hip muscles, they affect frontal-plane hip and knee kinematics minimally during running or jump-landing activities. Rather, providing feedback regarding movement performance in addition to strength training seems to produce greater changes in frontal-plane kinematics than hip-strengthening programs alone.

The study had inherent limitations. First, participants were healthy and without lower extremity pathology. Women with patellofemoral pain syndrome, for example, exhibit lower isometric strength than women without pathology. The extent to which neuromuscular control in the gluteus maximus is associated with frontal-plane knee motion may differ in participants with pathology at

### Table 2 Summary of Hierarchical-Regression Analyses on the Frontal-Plane Knee Angle

<table>
<thead>
<tr>
<th>Variable</th>
<th>$R^2$</th>
<th>$\Delta R^2$</th>
<th>$\beta$</th>
<th>$p$</th>
<th>$r$</th>
<th>Partial $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip angles</td>
<td>.478</td>
<td>.478</td>
<td>-0.095</td>
<td>.207</td>
<td>-204</td>
<td>-146</td>
</tr>
<tr>
<td>Sagittal plane</td>
<td></td>
<td></td>
<td>-0.225</td>
<td>.111</td>
<td>.222</td>
<td>-289</td>
</tr>
<tr>
<td>Transverse plane</td>
<td></td>
<td></td>
<td>0.795</td>
<td>&lt;.001</td>
<td>.672</td>
<td>.724</td>
</tr>
<tr>
<td>Hip-extensor strength</td>
<td>.570</td>
<td>.092</td>
<td>0.349</td>
<td>&lt;.001</td>
<td>.215</td>
<td>.471</td>
</tr>
<tr>
<td>Gluteus maximus recruitment</td>
<td>.603</td>
<td>.033</td>
<td>0.187</td>
<td>.016</td>
<td>.131</td>
<td>.277</td>
</tr>
</tbody>
</table>

Note: $R^2$ = cumulative proportion of variance in the frontal-plane knee angle accounted for by variance in the independent variable; $\Delta R^2$ = change in $R^2$; $\beta$ = standardized regression coefficient; $p$ = significance of $\beta$; $r$ = Pearson product–moment correlation coefficient between the independent variable and frontal-plane knee angle; partial $r$ = partial correlation between the independent variable and frontal-plane knee angle, controlling for the other independent variables.
Figure 1 — Partial correlations between frontal-plane knee kinematics and (A) transverse-plane hip kinematics, (B) hip-extension strength, and (C) gluteus maximus recruitment during a bilateral jump-landing task.

Second, the measures used may not best represent hip muscle function. For example, muscle-force production is greatest during eccentric contractions, and given that data were analyzed during the eccentric phase of the jump-landing cycle, the relationship between frontal-plane knee kinematics and hip-extensor strength may have better been assessed using eccentric-strength tests with an isokinetic dynamometer. Similarly, other measures of neuromuscular control such as recruitment timing...
and average recruitment during the jump-landing task may have provided different insight than examining peak recruitment. Last, variance in transverse-plane hip kinematics, hip-extensor muscle strength, and gluteus maximus recruitment accounted for approximately 60% of the variance in frontal-plane knee kinematics, meaning nearly 40% of the variance in frontal-plane knee kinematics remains unexplained. Clearly other factors need to be considered. Despite these limitations, we believe that the study’s findings are relevant for rehabilitation practitioners.

Future work should address some of the limitations identified in this study. For example, examining the timing of gluteus maximus recruitment and its association with hip and knee kinematics during a jump-landing task may provide additional insight into the extent to which neuromuscular control of the muscle contributes to lower extremity mechanics. Furthermore, methods used in the study should be expanded to simultaneously investigate the role of the gluteus medius in addition to the gluteus maximus—and to analyze their unique contributions to lower extremity mechanics—since functional deficits in both muscle groups have been theorized to contribute to excessive knee valgus.6–10,14,15

**Conclusion**

Hip kinematics in the transverse plane of motion correlated strongly with frontal-plane knee kinematics during a bilateral jump-landing task in healthy, active women. When hip kinematics were controlled statistically, variance in both hip-extensor strength and gluteus maximus recruitment also contributed to the variance in frontal-plane knee kinematics. An increase in knee valgus during the jump-landing task was associated with reduced hip strength and with reduced gluteus maximus recruitment during the activity. These findings imply that muscle strength and neuromuscular control are distinct elements of gluteus maximus function that should be considered when clinicians develop exercise programs designed to influence lower extremity mechanics during a dynamic motor task.

**References**


