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# Crossover Cutting During Hamstring Fatigue Produces Transverse Plane Knee Control Deficits

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***Objective***: To assess the effects of eccentric work-induced hamstring fatigue on sagittal and transverse plane (axial) knee and ankle biodynamics and kinetics during a running crossover cut directional change (functional pivot shift).

***Design and Setting***: A pretest-posttest, single-group intervention experimental design was employed. All data were collected in a biodynamics laboratory.

***Subjects***: Twenty healthy athletic females were trained for 3 weeks in crossover cutting before testing.

***Measurements***: Data were sampled during 3 unfatigued and 3 fatigued (20% eccentric isokinetic knee-flexor torque reduction) crossover cut trials. Three-dimensional kinematic and ground reaction-force data were sampled at 200 Hz and 1000 Hz, respectively, and joint moment estimates were calculated. Data were standardized to initial force-plate heelstrike for comparisons of mean differences between conditions using paired *t* tests with Bonferroni adjustments. Pearson product-moment correlations compared kinematic and eccentric hamstring-torque relationships.

***Results***: During internal rotation phase I, between heelstrike and impact absorption, mean internal rotation velocity increased by 21.2°/s ± 114°/s. During internal rotation phase II, mean peak transverse plane knee rotation during propulsion decreased by 3.1° ± 9°. During internal rotation phase II, mean peak ankle plantar flexor moment onsets occurred 12.7 ± 53 milliseconds earlier, and this activation demonstrated a moderately positive relationship with the onset of mean peak knee internal rotation during propulsion and a weak negative relationship with mean peak hamstring torque/lean body weight.

***Conclusions***: The increased knee internal rotation velocity during phase I indicates transverse plane dynamic knee-control deficits during hamstring fatigue. Earlier peak ankle plantar-flexor moments and decreased internal rotation during phase II in the presence of hamstring fatigue may represent compensatory attempts at dynamic knee stabilization from the posterior lower leg musculature during the pivot shift portion of the crossover cut. The weak relationship between decreased hamstring torque/lean body weight and delayed knee internal rotation during propulsion further supports greater dependence on ankle plantar flexors for dynamic knee stabilization compensation.

***Key Words***: biomechanics, injury mechanisms, functional movement assessment

Noncontact mechanisms may account for up to 78% of anterior cruciate ligament (ACL) injuries,[1,2] and athletic females are at particular risk. Numerous investigators have reported increased knee injury incidence for females in sports such as soccer,[3] team handball,[4] and basketball.[5–8] Multiple factors, including less muscular power,[9] more frequent lower extremity anatomical malalignment,[10] increased knee joint laxity,[10,11] hormonal influences on knee joint laxity,[12] and poor fundamental motor skills caused by poor training during the developmental years[11] have all been associated with this increased ACL injury incidence.

The crossover cut is a running directional change that is reportedly one of the most hazardous noncontact situations for the knee ligaments.[13] Crossover cutting demands coordinated lower extremity muscular activation to dynamically control the knee through rapid triaxial joint deceleration during the impact forces of initial ground contact and then during the ensuing rapid acceleration of forward propulsion in a new running direction. The stresses placed on the knee during crossover cutting have led to its being described as the functional equivalent of a clinical pivot shift maneuver.[14] The crossover cut is executed by planting the foot ipsilateral to the new running direction (Figure 1) and then crossing the contralateral lower extremity anteriorly to provide acceleration in the new running direction (Figure 2). Directional momentum change occurs during the plant-and-cut phase of the crossover cut. As terminal deceleration from the approach direction occurs over the planted foot, the pelvis and trunk are rotated toward the new direction. Following this, the contralateral lower extremity swings in the new direction to assist with acceleration. The

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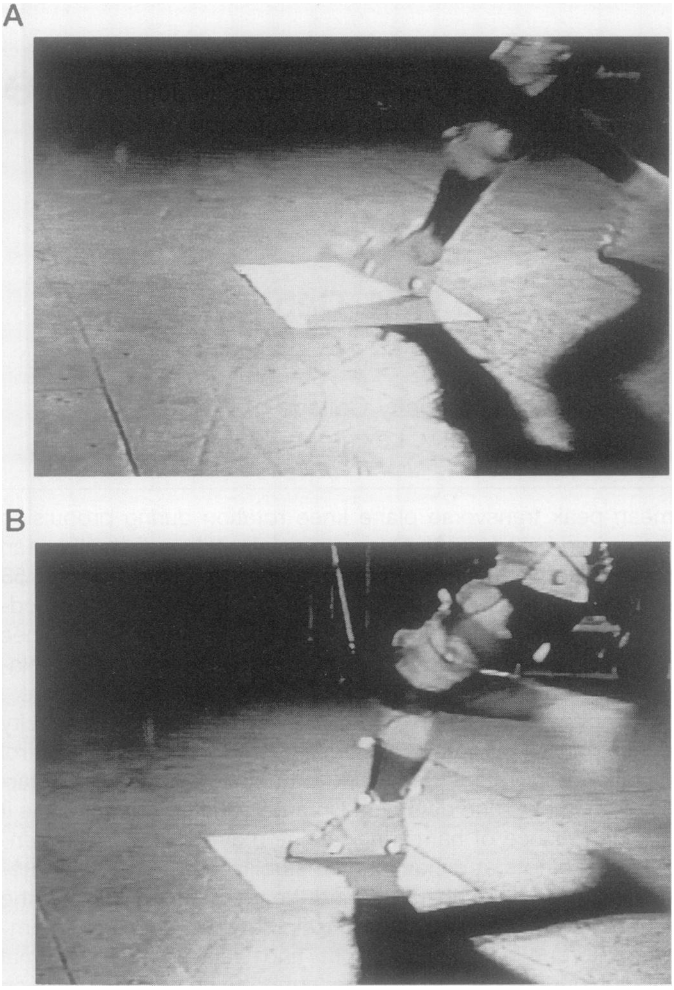

**Figure 1. A, Crossover cut initiation with heelstrike. B, Crossover cut impact absorption.**

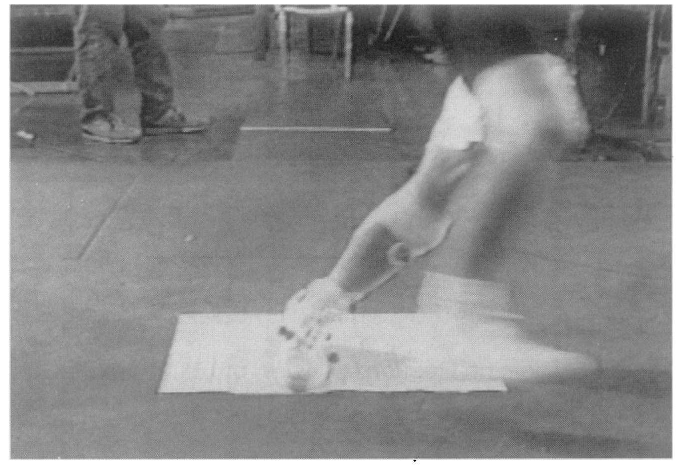

**Figure 2. Crossover cut pivot, attempting to execute a 90° cut (starting position in background at the taped line 2.5 m from center of force plate).**

stance lower extremity, after completing its deceleration function and after the pelvis and torso have been rotated, provides the primary acceleration force in the new direction.[13]

The hamstring muscles serve as dynamic ACL synergists providing joint-control forces primarily in the sagittal and transverse planes, with greater contributions to dynamic knee stability at ≥25° of flexion.[15–20] In the transverse plane, the hamstrings help to provide dynamic control of internal and external tibial rotation. During closed kinetic chain tasks such as crossover cutting, the hamstrings are assisted in sagittal and transverse plane dynamic knee control by the quadriceps femoris and proximal hip and distal lower leg musculature.[13,21,22]

Eccentric muscle activation is vital to dynamic joint stability,[23,24] and the hamstrings work in concert with the ACL in both the sagittal and transverse planes.[25–27] Anterior translation and internal rotation of the tibia normally occur as coupled motions,[28] and fatigued or weak hamstrings would theoretically be less effective in controlling the magnitude or velocity of either of these potentially ACL-injurious motions.

Using a 3-dimensional mathematical model to assess the transverse plane rotational restraints in 4 cadaveric knee joints, Blankevoort and Huiskes[29] found that the ACL was tensioned mainly by an internal rotation moment ($P < .05$). They further stated that the relative inclinations of the medial and lateral tibial surfaces caused an axial translation (traction effect) to be coupled to the axial rotation, whereby the tibial and femoral insertions of the ACL moved farther apart during internal knee rotation, resulting in further tensioning. Using a cadaveric sample of 14 knees, Andersen and Dyhre-Poulsen[30] reported that the ACL was an important restraint to internal rotation, particularly between 10° and 30° of flexion. Based on these findings, the internal knee rotation demands of crossover cutting would be particularly stressful to the ACL and the anterolateral capsuloligamentous structures. The purpose of our study was to determine the effects of eccentric work-induced hamstring fatigue on knee and ankle kinematics and net joint moment magnitudes and timing during the stance phase of a crossover cut.

## METHODS

### Instrumentation

**Video analysis system.** Four high-speed video cameras (NAC Model HVRB-2000, NAC Inc, Tokyo, Japan) sampled interlaced image-field data at 200 Hz. Two cameras were positioned on opposite sides of a runway so that each marker could be viewed by at least 2 cameras, as required by the direct linear transformation procedure.[31] A VP-310 Data Acquisition System (Motion Analysis Corp, Santa Rosa, CA) interfaced with a Sun 3/260 minicomputer (Sun Microsystems Inc, Mountain View, CA) phase locked the cameras to enable synchronized data collection. All data were analyzed using KinTrak version 3.0 software (Motion Analysis Corp).[32] Local segmental coordinate system and joint dimension data were collected and processed using Expert Vision software version 2.01 (Motion Analysis Corp).[33]

**Force plate system.** Ground reaction forces were sampled concurrently with kinematic data using a piezoelectric force plate (Model 9261A, Kistler Instrumentation Corp, Winterthur, Switzerland). Vertical (Z), anterior-posterior (X), and medial-lateral (Y) ground reaction force analog signals were digitally sampled at 1000 Hz. Amplified analog signals were input to an analog-to-digital board (Model 2, 821-F-16SE, Data Translations, Marlboro, MA) and digitally stored on a minicomputer.

## Subjects

Twenty healthy college-aged females who were involved in intramural athletics (soccer, basketball, flag football, or tennis) participated in this investigation. Subjects ranged in age from 18 to 23 years (mean = 21.1 ± 1.6), in weight from 50.8 to 63.5 kg (mean = 60.1 ± 3.6 kg), and in height from 149.9 to 172.7 cm (mean = 163.3 ± 5.7). Subject lean body weight was determined using triceps brachii and iliac crest skinfolds and the Sloan formula No. 2 for females (Skyndex Electronic Bodyfat Calculator, Caldwell, Justiss & Company, Inc, Fayetteville, AR). Mean subject lean body weight was 46.1 ± 2.7 kg. Subject weight was limited to ≤63.5 kg, given the limited eccentric torque capacity of our isokinetic device (Biodex Clinical Data Station Model 892–905, Biodex Corp, Shirley, NY). Only individuals who passed a low back and lower extremity injury screening were allowed to participate. Stance lower extremity preference was deemed the lower extremity that subjects chose for stance when attempting a soccer kick. For ease of data collection and analysis, only individuals with left stance limb preference participated in this study. Subjects were also questioned regarding the regularity of their menstrual cycles and oral birth control use. All subjects had regular menstrual cycles. Subjects were scheduled so that data collection took place intermenses to negate hormonal influences on ACL cellular metabolism.[12] Before participating, subjects were informed of possible risks and signed a consent form. This study was approved by the University of Kentucky Medical Internal Review Board.

## Preactivity Warm-up

Crossover cutting was preceded by subjectively low-intensity stationary cycling (Monark 817E, Quinton Fitness Equipment, Seattle, WA) at 2 kiliponds resistance (10 minutes), followed by bilateral static hamstring, ankle plantar flexor, hip adductor, trunk extensor, hip extensor, and quadriceps femoris stretching for 4 repetitions of 20 seconds' duration each. These activities were performed to promote normal neuromuscular function during cutting and to prevent injury.

## Crossover Cut Maneuver Training

For 3 days/week over 3 weeks before biodynamic testing, subjects were trained in the crossover cut technique (15 to 20 cuts/session) with emphasis on heelstrike landing and a cutting angle of as close to 90° from the approach direction as possible. During these sessions, a submaximal approach velocity of between 2 and 2.5 m/s (as determined by the primary investigator with a handheld stopwatch) over an approach distance of 2.5 m from the force-plate center was used to avoid injury during testing and to promote performance consistency.[34]

## Eccentric Isokinetic Hamstring Exercise Training

During the final week of crossover cut training, subjects were also trained in eccentric isokinetic hamstring work to become familiar with eccentric hamstring-activation timing, and the fixed speed-accommodating resistance concept of isokinetic exercise. During training and testing, an isokinetic velocity of 30°/s and a 305.2-N · m torque limit were used. Subject positioning, stabilization, and dynamometer input shaft gravitational moment corrections were performed using standard protocol.[35] Knee range of motion during isokinetic training and testing was between 30° and 90° of flexion as determined by the primary investigator with a handheld goniometer. This range of motion was used to enable consistent active input shaft torque initiation throughout the test range of motion (particularly at terminal extension) to avoid sudden stops and starts during the fatigue protocol. Knee-testing fixture lengths and pad positions were noted to ensure replication during the eccentric isokinetic hamstring-fatigue protocol. To isolate the hamstrings, the primary investigator applied manual resistance to the input arm (in the direction opposite the muscle group being tested, with a 40.7-N · m eccentric torque limit) to return the input arm to its starting position. This enabled the hamstrings to be trained or tested with minimal quadriceps femoris activation. This method replicated the fatigue protocol. Approximately 5 repetitions were performed during each training session.

During the last training session, mean peak eccentric hamstring torque was determined from 5 maximal effort repetitions (mean = 93.5 ± 9.5 N · m). The dynamometer was calibrated according to the manufacturer's protocol before data collection.[35] Subjects followed a consistent protocol with verbal encouragement to facilitate the desired volitional effort during all testing.

## Eccentric Isokinetic Hamstring Fatigue Protocol

Before initiating the fatigue protocol, subjects performed 3 maximal-effort repetitions to reconfirm their mean peak eccentric isokinetic hamstring torque and to create a horizontal cutoff cursor representing 80% of this maximal volitional effort (not observed by subjects). An eccentric fatigue model was selected to replicate the primary functional demands placed upon the hamstrings during the crossover cut stance phase. The exercise setting of Biodex Advantage software version 2.0.4 (Biodex Corp, Shirley, NY) was used during this protocol to enable investigator observation of each torque curve. Subjects performed continuous maximal effort repetitions until a 20% peak torque reduction was observed. Fatigue was operationally defined as a 20% torque reduction to provide a torque capability deficiency that was significant, but also safe and functionally relevant. Subjects were considered to have experienced 20% eccentric work-induced hamstring fatigue when 3 consecutive repetitions were less than 80% of the predetermined mean peak torque. Repetitions performed before hamstring fatigue ranged from 25 to 77 (mean = 45.4 ± 15).

### Retroreflective Marker Placement

Before cutting, subjects had 9 retroreflective markers secured to the left lower extremity, denoting the local segmental coordinate systems of the foot, leg, and thigh. Markers were placed so that each segment (foot, leg, and thigh) was defined by 3 markers.[22] A single marker placed near the fifth lumbar vertebra spinous process was used for calculating approach velocity. After crossover cutting trial data collection, subjects had 2 additional markers placed at the left hip, knee, and ankle to enable approximate joint center and segment length calculations within their respective local segmental coordinate systems (Figure 3).

### Video Field Calibration

Before data collection, a calibration file was collected, denoting the locations of known video field control points using KinTrak version 3.0 software (Motion Analysis Corp). These points consisted of 4 sets of 5 retroreflective markers (positioned at 15.2 cm, 45.7 cm, 76.2 cm, 106.7 cm, and 137.2 cm from the runway surface) suspended on strings (z-axis) from tripods positioned at the video field corners, defining a 1.22-m (x-axis) by 0.61-m (y-axis) spatial plane. We positioned 3 additional markers in a triangular pattern on the force-plate surface to identify its orientation within the global coordinate system (as defined by the control points) for subsequent inverse dynamic analysis. Spatial plane calibration used standard direct linear transformation procedures.[31]

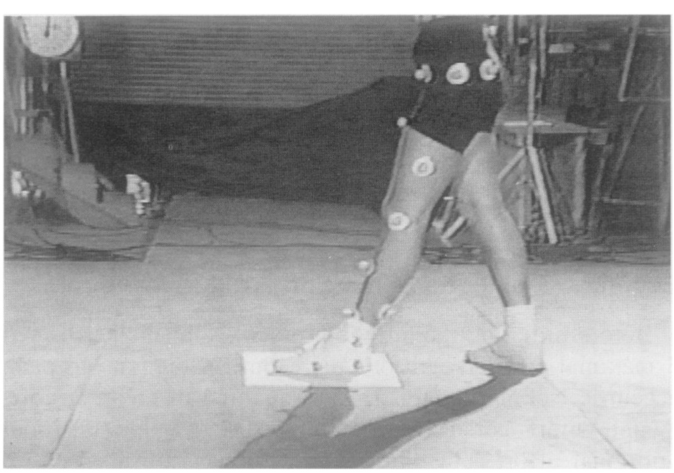

**Figure 3. Retroreflective marker placement.**

### Kinematic and Kinetic Analysis

Video calibration file and crossover cut trial tracking were performed using Expert Vision version 2.01 software (Motion Analysis Corp). A vector-transformation program converted calibration file data from a global coordinate system to an anatomically relevant local segmental coordinate system and determined approximate joint centers and thigh, leg, and foot segment lengths.[36] Following this, crossover cut trial data were tracked and input into the KinTrak program for kinematic analysis and then combined with ground reaction-force data to compute net joint moments using inverse dynamics. Standard KinTrak program approximations for center of mass, moment of inertia, and relative mass were used for net joint moment calculations.[32] We subsequently assessed mean differences between conditions for stance limb kinematic and kinetic variable magnitude and onset of occurrence at critical points during the crossover cut stance phase.

### Convention of Kinematic Description

Kinematic analysis defined complete knee extension as 0° and neutral ankle dorsiflexion as 90° (greater for increased dorsiflexion). Our biomechanical definition of neutral sagittal plane ankle position contrasts with the clinical definition of 0°. Transverse plane knee rotation was determined by the relationship of the leg to the thigh, such that neutral rotation was defined as 0°, relative leg internal rotation was negative, and relative leg external rotation was positive. Positive or negative net joint moments denoted the primary muscular activity occurring at a given joint relative to joint kinematics according to the right-hand rule.[37]

### Determination of Cutting Angle and Approach Velocity

The angle formed by the intersection of a line through the central portion of the lateral calcaneus and the fifth metatarsal head marker of the stance limb foot and the video field x-axis was used to approximate the cutting angle, such that toeing out was represented by an angle of less than 90° and toeing in was represented by an angle of greater than 90°. Approach velocity was calculated from fifth lumbar vertebra marker horizontal displacement at 0.25 milliseconds before force-plate contact.

### Design and Statistical Analysis

We collected data (3 trials unfatigued and 3 trials fatigued) on 5 subjects/week (4 groups of 5 subjects). Subjects wore the

Table 1. Cutting Intensity Indicators (mean ± SD)

| Variable | Unfatigued Hamstring | Fatigued Hamstring |
|---|---|---|
| Approach velocity | 2.34 ± 0.2m/s | 2.32 ± 0.3 m/s |
| Cutting angle | 86.1° ± 6° | 87.1° ± 7° |
| Impact knee flexion | 19.3° ± 9° | 19.8° ± 10° |
| Peak knee flexion | 57.8° ± 9° | 57.3° ± 10° |
| Peak impact vertical ground reaction force | 1213.1 ± 248 N | 1205 ± 285 N |
| Peak propulsion vertical ground reaction force | 1137.1 ± 160 N | 1148.6 ± 185 N |
| Force-plate duration | 356.7 ± 49 ms | 354.7 ± 51 ms |

same tennis shoe model and brand (Chris Evert Model, Converse, Inc, Reading, MA) for marker placement and shoe-force platform interface consistency.

Peak trial means and standard deviations for knee and ankle kinematic and kinetic variables were determined. Paired $t$ tests with Bonferroni adjustments for multiple comparisons assessed mean differences between unfatigued and fatigued conditions. Differences were deemed statistically significant when $P < .0167$ (0.05/3). Pearson product-moment correlations were used to compare kinematic and eccentric hamstring torque relationships. SAS for windows version 6.11 (SAS Institute Inc, Cary, NC) was used for all statistical calculations.

## RESULTS

Variables that reportedly relate to crossover cutting intensity[15,22,38] are presented in Table 1. Transverse plane peak knee and sagittal plane ankle kinematic data are presented in Table 2. Transverse plane kinematic analysis of the crossover cut revealed 2 distinct knee internal rotation phases after heelstrike in all trials. The initial knee internal rotation (Phase I) occurred immediately after heelstrike, before crossover cut directional change. This event is believed to represent sudden, distal-to-proximal kinematic changes as the forces of impact are attenuated. The magnitude and velocity of occurrence of these changes are largely dependent upon both the vigor of the cut and the ability of eccentric (deceleratory) lower extremity muscular forces to provide dynamic stability and protect noncontractile joint structures (Figure 4). A second knee internal rotation (Phase II) occurred as subjects attempted propulsion in the new running direction. This event is believed to represent the functional pivot shift portion of the crossover cut: the leg is maintained in relative internal rotation as the hip and thigh are externally rotated over the planted foot. Hamstring fatigue resulted in increased mean knee internal rotation velocity during phase I, decreased peak knee internal rotation during propulsion, and earlier maximal ankle plantar-flexor moment onsets (Table 2). The increased knee internal rotation velocity during Phase I suggests decreased or modified dynamic knee control in the transverse plane during impact-force attenuation. Hamstring fatigue resulted in earlier peak ankle plantar-flexor moment onsets, suggesting dynamic compensations to decelerate knee internal rotation during Phase II (propulsion), but not during Phase I (impact-force attenuation). The moderate positive correlational relationship between maximal ankle-dorsiflexion onset and maximal knee internal rotation during propulsion ($r = 0.71$, $P = .001$) supports this (Figure 5). The weak inverse relationship between mean peak hamstring torque/lean body weight and maximal knee internal rotation onset during propulsion ($r = -0.52$, $P = .03$) (Figure 6) further suggests an increasing contribution for dynamic transverse plane knee control from the ankle plantar flexors during hamstring fatigue. Repetitions to fatigue did not correlate even weakly with any other variable.

## DISCUSSION

The similarities between conditions for cutting intensity indicator variables strengthen the argument that differences between conditions were related to the effects of hamstring fatigue on dynamic knee control and not merely subjects' attempts to volitionally avoid ligamentously stressful knee positions. Increases in knee internal rotation velocity immediately after heelstrike during impact attenuation (Phase I) indicate transverse plane dynamic knee control deficits during hamstring fatigue. As researchers have alluded to at the ankle and subtalar joint,[16,17,22,39] the sudden velocity increases associated with these displacements may be more related to ACL injury than the ultimate magnitude.[39,40] Controlled deceleration either through dynamic muscular activation[16] or via bracing (or other proprioceptive garments), properly fitting and supportive footwear, or foot orthoses[39] may be vital to ACL

Table 2. Transverse Plane Peak Knee and Sagittal Plane Ankle Kinematic Data (mean ± SD)

| | Mean Internal Rotation Velocity (Heelstrike Impact) | Maximum Knee Internal Rotation During Propulsion | Peak Ankle Plantar-Flexor Moment Onset |
|---|---|---|---|
| Unfatigued trial means | 260.6° ± 113°/s | −37.4° ± 10° | 213.6 ± 55 ms |
| Fatigued trial means | 281.8° ± 117°/s | −34.3° ± 9° | 200.9 ± 50 ms |
| *t* score | 2.1 | 2.5 | 2.2 |
| df | 19 | 19 | 19 |
| *P* | .014 | .012 | .016 |

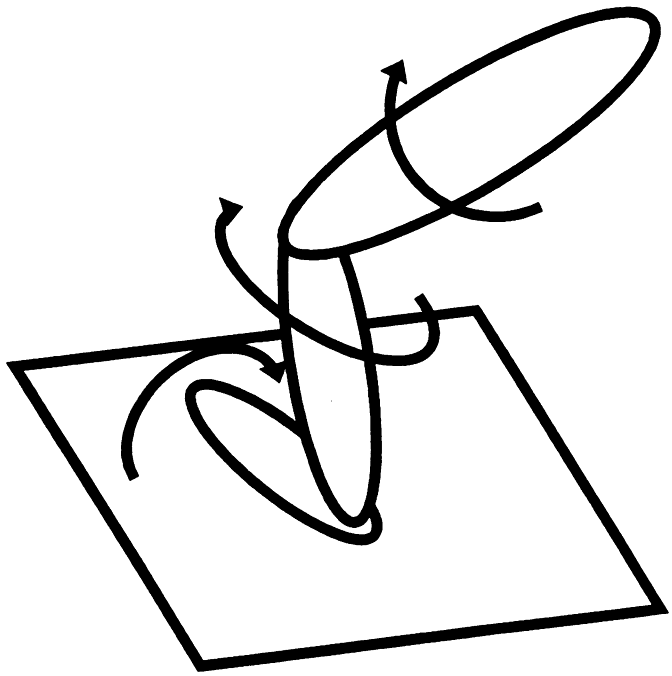

Figure 4. Lower extremity kinematics during impact-force attenuation (distal-to-proximal progression of subtalar eversion/ankle dorsiflexion, knee internal rotation, and flexion).

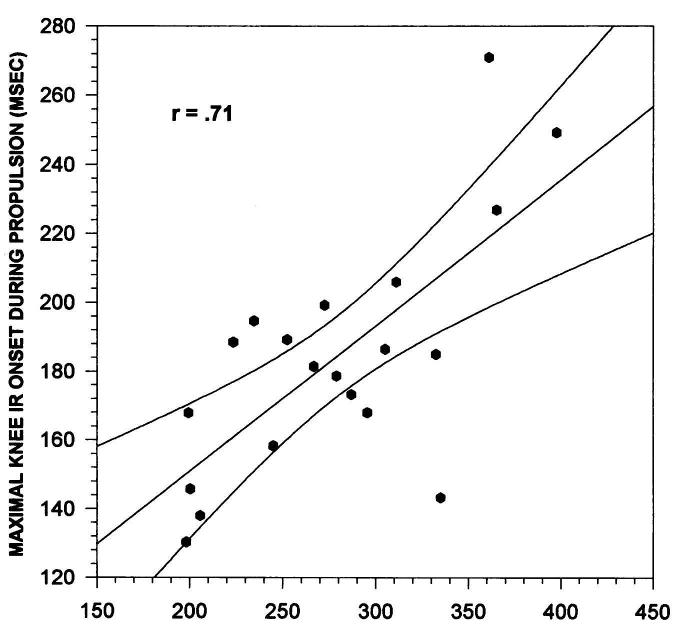


Figure 5. Maximal ankle dorsiflexion onset and maximal knee internal rotation (IR) onset during propulsion: correlation during hamstring fatigue (with 95% confidence interval).

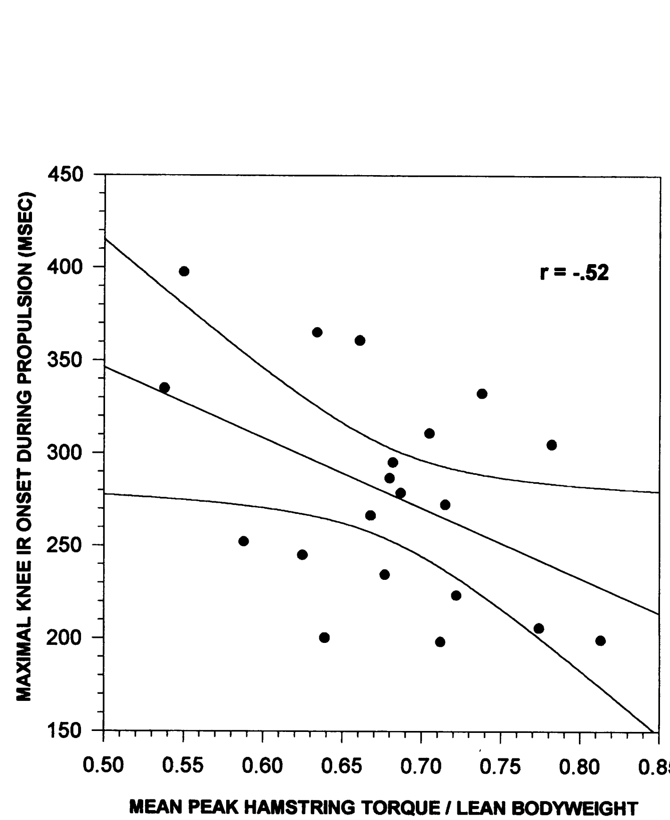


Figure 6. Mean peak hamstring torque/lean body weight and maximal knee internal rotation (IR) onset during propulsion: correlation during hamstring fatigue (with 95% confidence interval).

injury prevention. Earlier peak ankle plantar-flexor moment onsets and decreased knee internal rotation magnitude with propulsion (Phase II, functional pivot shift) during hamstring fatigue are believed to represent compensatory attempts at dynamic knee control from the lower leg musculature. These compensations, however, were not evident after hamstring fatigue for Phase I (impact-force attenuation), suggesting that compensations for dynamic knee control are either not necessary during this phase or are not attainable via neuromuscular means. The inverse relationship between mean peak hamstring torque/lean body weight and maximal knee internal rotation onset during propulsion with hamstring fatigue suggests that transverse plane knee control is being provided by another source, and our results in the aggregate strongly implicate the ankle plantar flexors. Based on these results, knee rehabilitation programs should attempt to restore normal synchronous knee and ankle arthrokinematics and neuromuscular activation timing before focusing on more conditioning-oriented strength and power capabilities. From an injury prevention standpoint, offseason conditioning programs may need to place greater emphasis on these components via sport- and position-specific functional movement challenges of progressive speed, cadence, duration, and distance.

## CONCLUSIONS

Eccentric work-induced hamstring fatigue created decreased dynamic transverse plane knee control, as evidenced by increased knee internal rotation during impact-force attenuation (Phase I). Earlier peak ankle plantar-flexor moment onsets and decreased knee internal rotation with propulsion (Phase II) during hamstring fatigue may represent compensatory attempts at dynamic knee stabilization during the reportedly ligamentously stressful functional pivot shift phase of the crossover cut. These compensations, however, were not evident during the knee internal rotation of impact-force attenuation (Phase I), suggesting that this phase is less controllable dynamically by neuromuscular activation. Although hamstring torque capability or endurance did not relate to improved transverse plane knee control, fatigue resistance of the lower leg musculature appears to be vital to this function. This lends support to knee rehabilitation and injury prevention programs that focus on coordinated lower extremity closed kinetic chain tasks, such as minisquats, single-leg vertical and horizontal hopping, lateral shuffles in a minisquat position, back pedaling, and quick multidirectional movement responses to cues. These tasks should be performed with the aforementioned progressions and with an emphasis on movement quality. When a movement lacks control, and when the athlete cannot correct by following verbal or visual cues, or both, the task should be stopped. Continued performance in the presence of faulty technique increases the likelihood of the athlete's sustaining a training-induced knee injury.

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