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Quadriceps Inhibition Induced by an Experimental Knee Joint Effusion Affects Knee Joint Mechanics During a Single-Legged Drop Landing

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Background: Arthrogenic quadriceps muscle inhibition accompanies knee joint effusion and impedes rehabilitation after knee joint injury.

Hypothesis: We hypothesized that an experimentally induced knee joint effusion would cause arthrogenic quadriceps muscle inhibition and lead to increased ground reaction forces, as well as sagittal plane knee angles and moments, during a single-legged drop landing.

Study Design: Controlled laboratory study.

Methods: Nine subjects (4 women and 5 men) underwent 4 conditions (no effusion, lidocaine injection, “low” effusion [30 mL], and “high” effusion [60 mL]) and then performed a single-legged drop landing. Lower extremity muscle activity, peak sagittal plane knee flexion angles, net sagittal plane knee moments, and peak ground reaction forces were measured.

Results: Vastus medialis and lateralis activity were decreased during the low and high effusion conditions ($P < .05$). However, increases in peak ground reaction forces and decreases in peak knee flexion angle and net knee extension moments occurred only during the high effusion condition ($P < .05$).

Conclusions: Knee joint effusion induced quadriceps inhibition and altered knee joint mechanics during a landing task. Subjects landed with larger ground reaction forces and in greater knee extension, thereby suggesting that more force will be transferred to the knee joint and its passive restraints when quadriceps inhibition is present.

Clinical Relevance: Knee joint effusion results in arthrogenic quadriceps muscle inhibition, increasing loading about the knee that may potentially increase the risk of future knee joint trauma or degeneration.

Keywords: muscle activation; swelling; knee; injury

Knee joint injury—whether acute,^{6,18,28} chronic,^{20,21,23,41} or experimentally induced^{7,13,14,26,27,34}—results in weakness of the quadriceps musculature acting about the knee joint

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complex. This phenomenon has been termed arthrogenic muscle inhibition (AMI)³⁸ and is defined as an ongoing reflex inhibition of musculature surrounding a joint after distension or damage to structures of that joint.¹¹ Arthrogenic muscle inhibition is the body’s innate response intended to protect the joint from further damage by discouraging its use. This protective mechanism comes at a high cost, because it restricts full muscle activation and thereby prevents restoration of strength,^{16,18,19} possibly placing patients at greater risk for reinjury^{38,49,50} and potentially predisposing them to chronic degenerative joint conditions.^{2,3,40}

Often patients return to sport and recreational activities with some degree of quadriceps AMI present ($\leq 20\%$),²⁹ despite the fact that functional and neuromuscular deficits

may still exist. Although several investigations have been conducted to examine the presence or absence of AMI after injury or disease,^{1,2,6,8,12,17,18,21,23-25,30,31,35-37,39,41,51} little attention has been paid to its consequences.^{15,21,44,45} To return athletes to competition safer and stronger, and to minimize the risk for reinjury and future joint degeneration, we must understand the neuromuscular deficiencies that occur as a result of injury and effusion.

Proper muscle function is of the utmost importance in knee joint stability.^{9,10,46-48} Loads applied across the knee are resisted through a combination of active and passive restraints. At lower loads, the passive restraints provide sufficient stability; however, during weightbearing tasks and sporting activities, joint forces are much greater, emphasizing the role of active muscles in maintaining adequate joint stabilization.^{5,33} Persistent quadriceps weakness would intuitively compromise knee joint stability by hindering the active restraints needed to protect against external loads, increasing the athletes' risk of injury and/or joint degeneration. The quadriceps musculature is critical in arresting downward body motion when landing from a jump. The eccentric contraction induced is capable of generating forces 2 times that of the isometric peak and is a largely efficient way to dissipate forces from impact. If the quadriceps muscle is inhibited, its ability to absorb energy should be affected and promote higher force transmission to the passive restraints.

Little work is currently available to the orthopaedic and rehabilitation communities that explores the potential negative effects that may result when athletes return to sport with AMI. Therefore, the overall purpose of this study was to determine whether an experimental knee joint effusion leads to quadriceps inhibition and affects landing mechanics. When quadriceps inhibition was present, it was expected that subjects would display reduced peak knee flexion angles and net peak knee extension moments, as well as higher peak ground reaction forces.

MATERIALS AND METHODS

Experimental Design

This investigation employed a crossover study design. The independent variable was effusion condition (no, lidocaine, low, high). The dependent variables were muscle activity, as measured by the root mean square (RMS) of electromyography (EMG) recordings; peak sagittal plane knee angles; peak ground reaction forces (GRF); and peak net sagittal plane knee moments.

Subjects

Nine healthy, recreationally active (Tegner score 5 or 6) subjects (4 women and 5 men; age, 23.4 ± 4.5 years; height, 67.5 ± 4.1 cm; mass, 69.4 ± 15.1 kg) volunteered to participate. Volunteers had not suffered any previous knee injury, had not undergone any prior knee surgeries, were not suffering from any current knee pain, and had not experienced any lower extremity injury in the previous 6 months.

Informed consent was obtained from all subjects and approved by the University's Institutional Review Board before commencement. After informed consent was gathered, age, height, weight, and dominant leg were recorded. The dominant leg was determined by asking each subject which leg he or she would use to kick a ball.

Instrumentation

The movements of the lower extremity segments were tracked with a 3-dimensional motion capture system (Vicon MX, Oxford Metrics Ltd, Oxford, United Kingdom). A model of the lower limb was delineated by 18 retro-reflective markers secured to each subject's dominant limb (Figure 1) that defined segment coordinate systems in reference to the fixed, global coordinate system. Six cameras captured lower extremity motion at a frequency of 120 Hz. Both static and dynamic calibrations were performed, and residuals of <2 mm from each camera were deemed acceptable.

Subjects landed on a force platform (OR 6-7; Advanced Medical Technology, Inc, Watertown, Mass) that was located in the middle of the capture volume for the cameras and used to collect GRF data. Ground reaction force data were sampled at 1080 Hz and were synchronized with the Vicon system for simultaneous collection. Force-plate data were filtered using a low-pass, anti-aliasing filter with a cutoff frequency of 1000 Hz.

To monitor muscle activity, the skin for each electrode site was shaved and cleaned with alcohol. Surface EMG electrodes (DE-2.1, Delsys Inc, Boston, Mass), spaced 10 mm apart, were secured over the muscle bellies of the quadriceps (vastus medialis, rectus femoris, and vastus lateralis), the hamstring (medial and lateral), and the gastrocnemius (medial and lateral) musculature. A single ground electrode was placed on the right ulnar styloid process. Raw, dynamic EMG and EMG gathered during maximum voluntary isometric contractions (MVIC) for each muscle group, hamstrings, quadriceps, and gastrocnemius, were collected with a commercial EMG system (Bagnoli 8-channel, Delsys) that was synchronized with the Vicon system and sampled at 1080Hz.

Testing Procedures

Testing Conditions. All subjects were asked to complete the drop landing procedures under 4 conditions (Table 1). Once the subjects were prepared and completed 3 to 5 drop landing practice trials, they were exposed to 1 of the 4 conditions listed in Table 1. After the intervention (or no intervention), subjects completed the drop landing protocol described below. The time from the induction of the joint effusion to the completion of the drop landings was about 2 minutes. All conditions were randomized and subjects underwent the conditions at least 3 days apart. For the randomization procedures, each subject was considered as a block, and the sequence of the conditions was assigned to each subject by way of a computer-generated random permutation.



Figure 1. Retroreflective marker placement. The medial knee and ankle markers and the left and right ASIS markers were only used during a static trial (to configure each subject with the global coordinate system) and were removed before the subject performed the dynamic landing trials. ASIS, anterior-superior iliac spine.

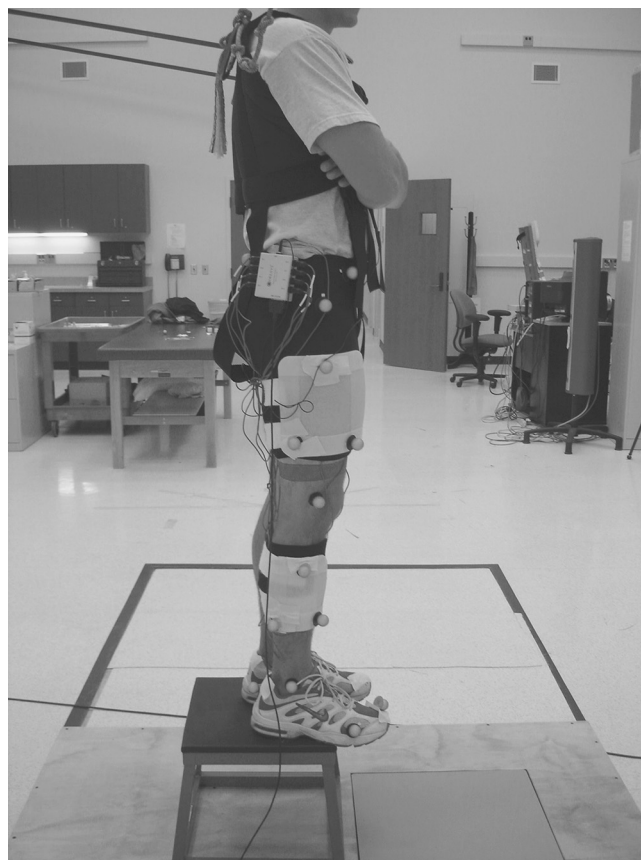


Figure 2. Starting position for the drop landing task.

TABLE 1
Description of the Interventions Provided to Subjects During the 4 Experimental Conditions

Condition	Intervention
No	No injections
Lidocaine	3 mL Xylocaine injected subcutaneously
Low	30 mL saline injected into knee joint capsule
High	60 mL saline injected into the knee joint capsule

Drop Landing Protocol. To simulate deceleration encountered during athletic participation, subjects were asked to perform a drop landing task, while secured in a safety harness, from a 30-cm height (Figure 2). The safety harness was used to secure subjects in case they were unable to stick the landing when impacting the ground. Subjects were given several practice trials before the intervention and were then asked to complete 5 successful trials after the intervention. A successful trial was defined as one in which the subject dropped down (did not jump down) on his or her dominant leg onto the force platform, stuck the landing for approximately

2 seconds, and did not touch the ground with the opposing limb. It should be noted that the landing strategy for the dominant and nondominant limb may be different. Since we chose to use the dominant limb in all testing sessions, some bias may have been introduced.

Joint Effusion Procedures. The area superolateral to the patella, bounded by the vastus lateralis, iliotibial band, and quadriceps tendon, of the dominant limb was cleaned with alcohol and povidone iodine. The subject's lower limb was extended while lying supine on a table. For the 3 intervention experimental conditions (lidocaine, low, high), a sterile, disposable syringe with a 25-gauge G 1.5-in needle, with 3 mL of 1% Xylocaine was injected subcutaneously only for anesthetic purposes. Care was taken not to enter the knee joint proper. During the low (30 mL) and high (60 mL) experimental conditions, subjects then had sterile saline injected into the knee joint capsule. We followed the procedures of Jackson et al²² to ensure good accuracy. Thirty milliliters of sterile saline was then injected during the low condition, while 60 mL of sterile saline was injected for the high condition.

Thirty and 60 mL of saline were chosen based on available data that illustrated the pattern of muscle shutdown with effusion.³⁴ Thirty milliliters has been shown to inhibit the vastus medialis, and 60mL inhibits the vastus medialis, vastus lateralis, and rectus femoris. Thus, we hypothesized

that when subjected to the low condition, volunteers would display less quadriceps inhibition than during the high condition.

Data Analysis. Marker trajectories were filtered with a fourth-order Butterworth low-pass filter with zero lag at a cutoff frequency of 6 Hz. Sagittal plane net knee joint moments were calculated using commercial software (Visual3D, C-Motion, Inc, Rockville, Md) combining kinematic marker and force platform data. Lower limb inertial properties were estimated based on anthropometric measurements of the subjects.⁵² The data convention is such that knee flexion and abduction angles/moments are denoted as negative. Peak knee flexion-extension angles, as well as peak net knee flexion-extension joint moments demonstrated during landing were recorded for all 5 trials and averaged for statistical analysis.

Electromyographic data were filtered with a fourth-order Butterworth high-pass filter with zero lag (cutoff frequency 20 Hz) to attenuate movement artifacts. Maximum voluntary isometric contraction data were processed with a 50-ms RMS moving window. The average amplitude of 3 MVIC was used to normalize the dynamic contractions collected during each drop landing. Dynamic EMG data, recorded during the drop landings, were processed with a 15-ms RMS window, normalized to the MVIC and multiplied by 100 to establish the percentage of the MVIC. Muscle activity was described by a 250-ms period after ground contact.⁴² Quadriceps, hamstrings, and gastrocnemius muscle activity demonstrated during landing were recorded for all 5 trials and averaged for statistical analysis.

Statistical Analyses. A one-way repeated measures multivariate analysis of variance was completed to determine if muscle activity, peak sagittal plane knee angles, peak GRF, and peak net sagittal plane knee moments differed between the conditions observed. Univariate F tests and Sidak's *t* multiple comparison procedures were used to make post hoc comparisons. The a priori alpha level was set at $P \leq .05$. Regression analyses were used to determine the effect of quadriceps muscle activation (vastus medialis, vastus lateralis, and rectus femoris) on the sagittal plane knee angles and moments as well as the GRF.

RESULTS

Average peak sagittal and frontal plane knee flexion angles, net sagittal plane knee moments, and peak GRF are listed in Table 2. Quadriceps, hamstrings, and gastrocnemius muscle activity is depicted in Figures 3 through 5. The overall multivariate analysis of variance revealed significant differences for condition ($F_{30,51} = 2.04$; $P = .012$).

Muscle Activity

Vastus medialis activity was greater in the no effusion (mean = 95.22) and lidocaine conditions (mean = 95.48) when compared with the low (mean = 68.24; $P < .05$) and

TABLE 2
Average Peak Knee Flexion Angles (KFA), Peak Net Knee Extension Moments (KEM), and Peak Ground Reaction Forces (GRF)

Condition	KFA (Mean \pm SD)	KEM*BW (Mean \pm SD)	GRF Nm/kg (Mean \pm SD)
No	-47.39 \pm 10.14	-1.61 \pm 0.954	43.27 \pm 5.40
Lidocaine	-46.05 \pm 7.90	-1.87 \pm 1.09	44.88 \pm 6.54
Low	-44.55 \pm 8.68	-2.02 \pm 2.00	44.97 \pm 7.29
High	-36.30 \pm 2.77	-3.37 \pm 1.43	55.26 \pm 6.22

SD, standard deviation; BW, body weight.

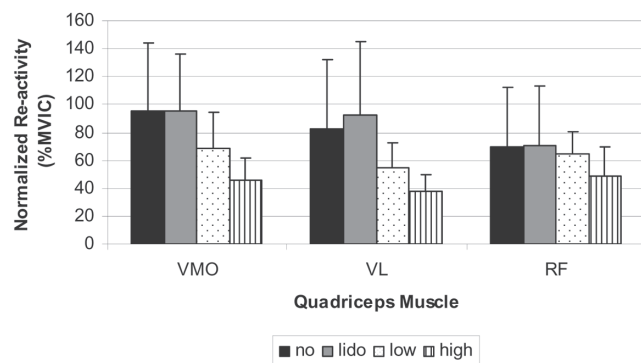


Figure 3. Average (\pm SD) quadriceps muscle activity during the landing task. SD, standard deviation; MVIC, maximum voluntary isometric contractions; VMO, vastus medialis; VL, vastus lateralis; RF, rectus femoris.

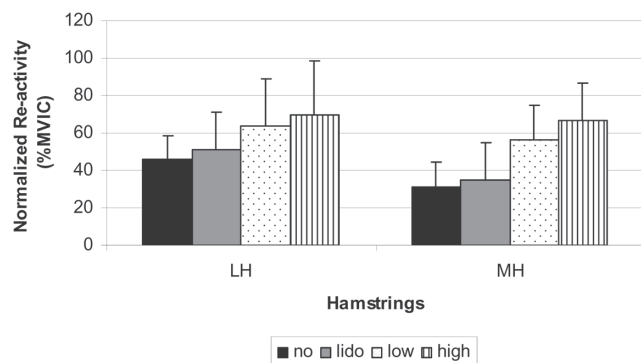


Figure 4. Average (\pm SD) hamstrings muscle activity during the landing task. SD, standard deviation; MVIC, maximum voluntary isometric contractions; MH, medial hamstrings; LH, lateral hamstrings.

high effusion (mean = 45.89; $P < .05$) conditions. Greater amounts of inhibition were noted for the high effusion condition when compared with the low effusion condition ($P = .03$). No difference existed between the no effusion and

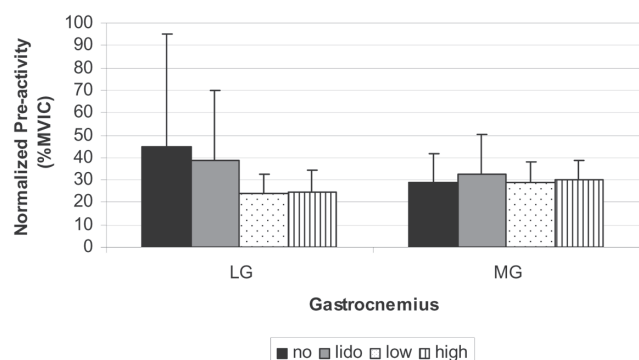


Figure 5. Average (\pm SD) gastrocnemius muscle activity during the landing task. SD, standard deviation; MVIC, maximum voluntary isometric contractions; MG, medial gastrocnemius; LG, lateral gastrocnemius.

lidocaine conditions ($P > .05$). The vastus lateralis followed the same pattern displayed by the vastus medialis. Vastus lateralis activity was greater in the no effusion (mean = 82.54) and lidocaine conditions (mean = 102.27) when compared with the low (mean = 54.71; $P = .03$) and high effusion (mean = 37.66; $P = .008$) conditions. Greater amounts of vastus lateralis inhibition were noted for the high effusion condition when compared with the low effusion condition ($P = .007$). No difference existed between the no effusion and the lidocaine conditions ($P > .05$). Medial hamstring activity was lower in the no effusion (mean = 32.54) and lidocaine conditions (mean = 35.05) when compared with the low (mean = 55.96; $P = 0.003$) and high effusion (mean = 66.86; $P = 0.001$) conditions. Medial hamstring muscle activity was also greater during the high effusion condition when compared with the low effusion condition ($P = .025$). No difference was noted between the no effusion and the lidocaine conditions ($P > .05$). Rectus femoris, lateral hamstring, medial gastrocnemius, and lateral gastrocnemius muscle activity were not found to differ between the 3 intervention conditions ($P > .05$).

Kinematics and Kinetics

The peak knee flexion angle during the high effusion condition was lower than that in the lidocaine and no effusion conditions ($P < .05$) but did not differ significantly from the low effusion condition ($P = .119$). No significant difference was noted between the no effusion and the lidocaine conditions ($P > .05$). The net peak knee extension moment during the high effusion condition was less than in the no effusion and lidocaine conditions ($P < .05$) but was not significantly different from the low effusion condition ($P = .09$). No significant difference was found for the net peak knee extension moment between the no effusion, lidocaine, and low effusion conditions ($P > .05$). The peak GRF during the high effusion condition was larger than in the no effusion and lidocaine conditions ($P < .05$) but did not differ significantly from the low effusion condition ($P > .05$). No significant difference was found for the peak ground reaction force between the no and low effusion conditions ($P = .975$).

During the high effusion condition, quadriceps muscle activity accounted for a significant portion of the variance in the sagittal plane knee angle ($R^2 = 0.285$; $P = .046$), sagittal plane knee moment ($R^2 = .369$; $P = .036$), and the vertical GRF ($R^2 = .825$; $P = .024$).

DISCUSSION

The hypothesis that quadriceps inhibition is partly responsible for altered kinetics and kinematics during a single-legged landing was supported by our data; surprisingly, these findings were only evident during the high effusion/inhibition condition. We expected the knee mechanics to change for the low effusion/inhibition condition as well because a significant amount of quadriceps inhibition was present. However, our results do appear to agree with those gathered while subjects jogged with a 20-mL induced effusion.⁴⁴ Quadriceps inhibition (vastus medialis and lateralis) was present with the effusion but no changes in the sagittal plane knee joint kinematic pattern were observed when the subjects jogged. Torry et al⁴⁴ attributed the lack of change to the high inertial forces that would be experienced by the lower limb during jogging. The inertia encountered may have been of sufficient magnitude to overcome the inhibition of the quadriceps musculature. This rationale could also be applied to our findings. A second possibility is that the muscle activation, provided by the uninhibited rectus femoris, may have been adequate, with the lower levels of vastus lateralis and medialis inhibition, to provide the necessary quadriceps control to maintain normal knee movement patterns during the impact. Yet a third possibility for the normal knee mechanics during the low effusion condition could be the heightened hamstring activation. With smaller amounts of quadriceps inhibition the hamstring facilitation experienced may be enough to stabilize the knee joint by restoring balance between the knee flexors and extensors.

Our data suggest that, in general, quadriceps inhibition induced by knee joint effusion results in a more extended knee during landing. Furthermore, it appears that AMI reduces the ability of the quadriceps to act as a mechanical restraint during joint loading, as evidenced by the reduced net knee extension moment. When completing a single-legged landing, the "stance" limb accepts full support of the body and relies on eccentric control of the quadriceps musculature to allow knee flexion so that shock attenuation is promoted. The increased peak GRF observed during the high effusion/inhibition condition suggests that shock attenuation was sacrificed and higher forces were likely transferred to passive joint structures.

A reduction in the net knee extension moment and knee flexion angle during weight acceptance in a gait cycle has been termed "quadriceps avoidance" and is thought to result from a reluctance or inability to completely activate the quadriceps muscles. Quadriceps avoidance gait patterns have been observed in patients with anterior cruciate ligament injury.⁴ This may minimize knee instability, by reducing anterior tibial translation, thereby preventing

episodes of giving way. Torry et al⁴⁵ elicited a quadriceps avoidance gait pattern with an induced knee joint effusion without any concomitant joint damage. Our findings suggest that quadriceps avoidance patterns occur with effusion, not only during walking gait as noted by Torry et al,⁴⁵ but also during a more dynamic, sport-specific movement, ie, landing from a jump.

It should be noted that the reduction in the net knee extension moment observed in our study could have resulted from the quadriceps inhibition and/or the hamstring facilitation. Our data show that the quadriceps muscle activation accounted for approximately 37% of the variance in the reduced knee extension moment (noted in the high effusion condition). For descriptive purposes, we added the medial and lateral hamstrings into our regression model along with the quadriceps musculature and the R^2 value increased to .42, suggesting that the hamstring facilitation was only able to account for 5% the variance. On the basis of these data, it appears that the reduced knee extensor moment is primarily the result of the quadriceps inhibition and not the medial hamstring facilitation. The remaining 58% of variance unaccounted for in our model could be due to numerous factors, including kinematic changes at the hip and ankle or the presence of the fluid in the knee joint, as well as other lower extremity muscle activity.

Quadriceps inhibition accompanies several knee pathologic conditions (anterior cruciate ligament injury, patellofemoral pain, and meniscal tears) and is related to knee osteoarthritis.^{25,31,32,43} It is plausible that the posttraumatic osteoarthritis associated with knee joint trauma could be at least in part caused by quadriceps inhibition.⁴⁰ Muscle forces are a major determinant of loading patterns across a knee joint's surface. Decreasing the muscle forces acting about a joint, via injury or effusion, will ultimately affect loading conditions, as seen in our study. The quadriceps musculature has a protective function, serving as shock absorber capable of dampening loads during activity. Failure to adequately absorb forces about the knee can cause increased loading of the articular cartilage, which may result in progressive degeneration. Since quadriceps muscle inhibition may be one culprit in initiating knee osteoarthritis, care should be taken to restore quadriceps activation before returning patients to sports or recreational activity. This same caution should also apply to returning patients to activity with a joint effusion, as effusion results in muscle weakness. Failure to restore normal muscle function may alter normal loading patterns and initiate joint degeneration.

It could be argued that the muscle inhibition displayed after the induced effusion was due to pain. The procedures used to induce knee effusion have been previously found not to be perceived as painful.¹³ No subjects participating in this study described pain while landing. However, subjects did typically describe a feeling of fullness or tightness during the high effusion condition.

Clinically speaking, our data may provide some insight as to the significance of returning an athlete to sport with an effusion. Our data suggest that a smaller effusion (30 mL) did not alter biomechanics around the knee joint, and thus it may be safe to return a person to sport with a minimal effusion. However, it is important to note that the induced effusion is noninflammatory in nature and thus is very different than

the effusion that would result from trauma, disease, or surgery. Caution should be exercised when generalizing our results to athletes with painful, swollen, and inflamed knees.

CONCLUSIONS

A knee joint effusion results in quadriceps inhibition and alters knee joint kinetics and kinematics during a landing task. Subjects landed with a more extended knee posture, which appeared to interfere with the ability of the knee to absorb shock during the impact, as observed via the higher GRF. Persons with weak quadriceps muscles appear to alter landing mechanics, causing larger forces to be transferred to the knee. Rehabilitation protocols before return to sport should focus on restoring quadriceps muscle function.

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