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DYNAMIC SAGITTAL-PLANE TRUNK CONTROL DURING ANTERIOR CRUCIATE LIGAMENT INJURY

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Abstract

Background—Recent studies have demonstrated that trunk control likely plays a role in anterior cruciate ligament (ACL) injury. Yet, the majority of ACL research remains focused on the lower limb, with limited information on the trunk position at the time of injury.

Hypotheses—Athletes experiencing a non-contact ACL-injury, after a one-legged landing, position their center-of-mass (**COM**) more posterior from the base-of-support (**BOS**) at initial ground contact, in comparison to uninjured athletes. The distance from the **COM** to the **BOS** (**COM_BOS**) is larger in female, as compared to male, athletes during one-legged landing.

Study Design—Case control study; Level of evidence, 3

Methods—Movie captures of 20 athletes performing a one-legged landing maneuver, resulting in a torn ACL were compared to matched (for gender, sport, and activity just prior to landing) movie captures of 20 athletes performing a similar maneuver that did not result in an ACL disruption (controls). The **COM_BOS**, trunk_G angle, and limb_G angle (both relative to the gravity vector) were measured in the sagittal plane at initial ground-foot contact. A two-way ANOVA (injury_status×gender) were used to examine the hypotheses.

Results—There was a significant difference in all 3 measures based on injury_status, but not on gender. **COM_BOS**, normalized by femur length, and limb_G angle were greater (Δ=0.9, p<0.001 and Δ=16°, p=0.004, respectively) and the trunk_G angle was smaller (12°, p=0.016) in the subjects that sustained an ACL-injury as compared to controls. The average **COM** was calculated as 38 cm more posterior relative to the **BOS** in the subjects who sustained an ACL-injury as compared to controls.

Conclusions—Landing with the **COM** far posterior to the **BOS** may be a risk factor for noncontact ACL-injury and potentially can be addressed in prevention programs.

Keywords

ACL-injury; injury prevention; gender differences

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INTRODUCTION

Anterior cruciate ligament (ACL)-injuries are typically sports related, occur in active healthy young adults (15–24 years old), involve expensive intervention with long recoveries, and result in many athletes losing knee function and quality of life[24,26,31]. For these reasons a sustained and extensive research effort has been put forth to identify the risk factors associated with ACL-injuries as a first step in trying to prevent them[2]. This efforts has tended to focus on the lower limb[5,11,15,27,30,37], yet more recent work has begun to focus on trunk orientation and control[4,20,30,38].

The control of sagittal-plane trunk position may play a key role in ACL-injury, as it is central to balance control. The importance of trunk control in ACL-injury is evidenced by the phantom-foot mechanism in skiing, which partially attributes ACL-injury to a strong quadriceps contraction[13]. This mechanism was tested using a 2D sagittal plane model of landing during high-speed downhill skiing[14]. When a small balance disturbance caused a slight backwards fall, ACL forces large enough to cause failure were seen during the model's attempt to restore balance. A recent descriptive videotape study supported this finding in noting that athletes who sustained an ACL-injury were leaning backwards at the time of injury[7]. Blackburn and Padua[4] demonstrated that increased trunk extension (measured as the angle between the trunk and the thigh) during a two-legged drop landing increased the ground reaction and quadriceps forces. Similarly, Kulas and colleagues[20] demonstrated that subjects who increased trunk extension (measured as the angle between the trunk and vertical line) in response to an additional trunk load during a 2-legged drop-test , implemented a quadriceps dominant strategy (i.e, there was an increase in quadriceps and a decrease in hamstring forces) upon landing. These 2D sagittal plane studies indicate that when the trunk is more extended during a landing maneuver, the quadriceps are recruited in an attempt to maintain balance.

In opposition to these modeling and lab-based studies, an earlier video-based study[8] found that the hip angle (measured as the angle between the trunk and the thigh) was significantly more flexed at foot contact during a one-legged landing maneuver that resulted in an ACL disruption (provocative landing position), as compared to a safe landing position. Therefore, the actual orientation of the trunk relative to the leg may not be as important as the position of the trunk relative to the foot, which is influenced not only by the trunk angle, but the hip, knee, and ankle angles as well. If the gravitational vector from the body's center of mass (**COM**, approximately located at the center of the trunk) does not lie within the base of support (**BOS**) then static posture is unstable[18,19]. In order to avoid a fall, the body's posture must be altered so that the **COM** falls within the **BOS**. In a dynamic situation, the **COM** can fall outside the **BOS**, but if the distance is too great, then recovery is no longer possible, resulting in a fall.

This study tested the hypothesis that the distance from the **COM** to the **BOS** (**COM_BOS**) was larger at the time of initial ground contact in the provocative, as compared to the safe, landing position. In addition, the hypothesis that limb angle relative to vertical (limb_G angle) was larger, but trunk angle relative to vertical (trunk_G angle) was no different, in the provocative, as compared to the safe, landing position was also tested. The analysis was limited to the sagittal plane, as the trunk position in the frontal plane had previously been reported[17]. Since female athletes tend to injure their ACL more frequently than their male counterparts[3] a tertiary hypothesis was tested: The **COM_BOS** and limb angle were larger in the female athletes as compared to the male athletes, during a one-legged landing maneuver.

METHODS

Twelve videotapes of athletes captured during an ACL-injury, acquired for a previous study[8], formed the basis of the current study. Sixteen additional movies in digital format were acquired from collaborators and the public domain. For a video or movie clip to be included within the study it had to meet previously published inclusion criteria[8]. The same author (AU3) assessed both the original videos, as well as the additional movie clips (eight additional movie clips met the inclusion criteria), resulting in a total of 20 movie clips of athletes performing a one-legged landing maneuver that resulted in an ACL-injury (Table 1). All ACL-injuries were confirmed based on the medical record, except two. These two videos were acquired directly from the public domain and the ACL-injury was confirmed through media reports. The same author (AU3) assessed fifty sagittal view videotapes (12 were from a previous study[8]) or digital movie clips of athletes (controls) performing similar decelerating or landing maneuvers during game situations that did not result in an ACL tear (32 met the inclusion criteria). The activity being performed just prior to ground contact was categorized into one of three activities: 1) stopping from a run (run-stop), 2) a vertical jump, or 3) a horizontal jump. From these 32 control clips, 20 were selected so that the controls were matched for gender, sport, and activity just prior to landing. To lessen any potential for selection bias, the matching was done without reference to the video data and the athletes' landing position did not factor into the acceptance or rejection of the video clip anytime during the selection process. This study was exempt from institutional review board approval, as assessed by the IRB of the National Institutes of Child Health and Human Services, NIH, as all movies were in the public domain.

The video recordings and digital movies were edited using Adobe Premiere Pro (version 2.0, *Adobe Systems, Inc., San Jose, CA*) and iMovie HD (*Apple, Cupertino, CA*), respectively. For each movie the frame in which the foot initially contacted the ground (initial contact) was captured and stored for analysis. This frame was distinguished from the series of frames capturing foot fall, by having a least a single point on the foot stop its downward progression. Image J (*National Institutes of Health, Bethesda, MD*) was used for all measurements. For consistency, a single author (AU2), who was not involved in assessing the video quality, performed all measures. Four months after the initial analysis, the measures were repeated by AU2, who was blinded to the initial results.

The first measure of interest was the **COM_BOS**. The **COM** was defined as the center of an ellipse delineating the athlete's trunk (Figure 1). The major axis was the centerline of the trunk (represented as the line from the center of the hip joint to the center of the shoulder joint) and the minor axis ran from the anterior to the posterior aspect of the trunk. The **BOS** was defined as the point bisecting the line of contact between the shoe and the floor at initial contact. To account for small variations in camera angle across images, perpendicular lines on the field of play (e.g., the key in basketball) were used to denote the anterior and medial directions relative to the athlete. The **COM_BOS** (in pixels) was then taken along the anterior/posterior direction. Since the conversion from pixels to mm was not available, the **COM_BOS** was normalized by femur length (measured from the center of the knee joint to the center of the hip joint), which was measured from the identical image as the **COM_BOS**. This scaling accounted for the variations in magnification factors and variations in subject height. In addition, any slight rotation of the athlete away from the sagittal plane would have resulted in a foreshortening of the **COM_BOS** (by the cosine of the out-of-plane rotation angle). A similar foreshortening of the femur_length would have also occurred. Thus, dividing the **COM_BOS** by the femur_length minimized this error. Femur length was chosen over subject height as the scaling factor, because this single measure was not prone to cumulative measurement errors and has been correlated with body height[21]. Two angles ($trunk_G$ and $limb_G$) were also measured. The $trunk_G$ angle was defined as the angle from the vertical to the centerline of the trunk. The $limb_G$ angle was defined as the angle between the vertical and the thigh (represented as the line from the center of the knee joint to the center of the hip joint). A positive $trunk_G$ and/or $limb_G$ angle indicated that the trunk and/or limb was rotated anteriorly relative to vertical.

An a priori power analysis revealed that seven subjects were needed for both the injured and control groups (alpha = 0.05, beta = 0.80). This was based on the assumption that the difference in the **COM_BOS** between the injured and control populations would be 0.246*height (Figure 2), and that the variation in both populations would be equal to 75% of the average value of **COM_BOS**. Thus, the original video tapes[8] ($n_{injured}$ = 12 and $n_{control}$ = 12) were sufficient to test the main hypothesis, but the additional digital videos were added in order to match the two cohorts and investigate difference across subpopulations.

A two-way analysis of variance (2×2 ANOVA, *SPSS 15.0, IBM Corporation, Somers, NY*) was used to assess main and interaction effects of injury_status and gender on three variables (**COM_BOS**, $limb_G$ angle, and $trunk_G$ angle). Intraclass correlation coefficients, using a two-way mixed effects model, were used to examine intra-rater reliability. A discriminant analysis determined if any single variable could distinguish injury_status. A *p*-value less than 0.05 was considered significant.

RESULTS

Matching was completely successful for the first two criteria (Table 1). But due to the difficulty in obtaining control movie clips that fit the inclusion criteria, two controls categorized as horizontal jump were matched with 2 injured subjects categorized as run-stop (all other parameters matched). No significant differences in any of the matching criteria were found between groups.

For the COM_BOS, $limb_G$ angle, and $trunk_G$ angle, the intraclass correlations coefficients were 0.956 (95% CI: 0.917-0.977), 0.988 (95% CI: 0.977-0.994), and 0.967 (95% CI: 0.937-0.983), respectively.

Injury_status was a significant main effect for **COM_BOS**, $limb_G$ angle, and $trunk_G$ angle (Table 2). The **COM_BOS**, normalized by femur length, was greater in the ACL-injured population (Δ=0.9, p <0.001, Figure 3). If an average height of 177.8 cm (5’ 10”) and a femur length of 0.245*height (Figure 2) is assumed for both groups, then on average the **COM** was 38 cm more posterior relative to the **BOS** in the subjects who sustained an ACL-injury as compared to controls [177.8*0.245*(**COM_BOS**$_{Controls}$ - **COM_BOS**$_{Injured}$), Table 2]. The $limb_G$ angle (Figure 4) was greater (Δ=16°, p=0.004) and the $trunk_G$ angle (Figure 5) was smaller (Δ=12°, p=0.016) in the ACL-injured, as compared to the control, population. Interestingly, the same trends existed if each sport was evaluated separately, but due to power issues, significant differences were only found for basketball.

Gender was not a significant main effect for any variable and there was no interaction effect between injury_status and gender for any of the three variables of interest. Specifically, differences did not exist when comparing male versus female athletes within or across the two cohorts.

The value of **COM_BOS** discriminated between athletes who sustained an ACL-injury and athletes that did not with 80% accuracy (Figure 6, Wilks’ Lamba, p<0.001). The $limb_G$ angle did less well in discriminating the groups (72%), whereas the $trunk_G$ angle could not discriminate the groups (70%). Using a combination of these variables did not improve the accuracy of discrimination.

DISCUSSION

This study demonstrates that having the **COM** far posterior to the **BOS,** a large $limb_G$ angle, and a small $trunk_G$ angle at initial ground contact are important components of the noncontact ACL-injury mechanism. These results extend our previously defined provocative and safe landing positions[8] in the sagittal plane. In the provocative position, the athletes tend to land flat-footed, with the hip flexed, knee extended, and the **COM** far posterior to their **BOS**. In the safe position, athletes land on their forefoot with the hip in a neutral position, the knee slightly more flexed, and the **COM** close to the **BOS**, based on a sagittal plane analysis. These results may be useful in screening athletes who are at risk for ACL-injury and for implementing a prevention program that trains athletes to land with the foot closer to the body. In addition, training athletes to fall safely when landing with the **COM** far posterior to the **BOS,** instead of reflexively activating their hip flexors and knee extensors, may help prevent ACL-injuries. Future studies are needed to determine if neuromuscular interventions that focus on improving core[35] stability and trunk positioning can help reduce the incidence of ACL-injuries.

Previous video tape studies[8,17] have failed to demonstrate significant coronal plane alignment (knee abduction, hip abduction, or trunk angle) differences at initial contact between the safe and provocative landing positions when comparing injured athletes to controls. Yet, other studies have demonstrated that increased knee abduction[16] and lateral trunk bend[17] during landing may be a risk factor for non-contact ACL injury in female athletes. Interestingly, the current study did not show significant differences between male and female athletes for any variable, indicating that a more posteriorly place trunk may be a generalized risk factor across genders.

A consensus is beginning to form around the concept that ACL-injury is likely due to a combination of forces. The critical force appears to be a compressive force on the lateral aspect of the knee[6,8,23,37], resulting in a sliding of the lateral femoral condyle on the lateral tibial plateau with resultant ACL disruption, often referred to as a buckling of the leg, instead of the normal knee flexion to absorb the ground reaction forces. Landing in an unstable posture may contribute to the ACL disruption by lowering the level of impulsive force required to buckle the leg and cause an ACL tear. The control subjects land with the ankle plantarflexed[8] and the **COM** less than a single foot length posterior from the **BOS**. Thus, they are close to a stable static posture and ankle dorsiflexion would extend the **BOS** towards the heel, creating a stable posture. In contrast, on average, the ACL-injured athletes land with the **COM** more than two foot lengths posterior to the **BOS** with a dorsiflexed ankle[8], creating a less stable position. To stabilize their posture, these athletes would likely try to flex their trunk forward by activating their quadriceps and trunk flexors[13,14]. This vigorous quadriceps contraction would lower the impulse force necessary to tear the ACL, by adding a compressive force, as well as, a secondary anterior shear force on the tibia[25,33]. This activation likely occurs prior to landing as the athletes prepare to stabilize their **COM** at the time of ground contact[10].

At the time of foot contact the trunk’s momentum would naturally rotate the trunk forward, even without core muscle or quadriceps activation. Since the foot lands in a dorsiflexed position (near the end range of motion) in the injured athletes[8], the rotation of the tibia cannot assist in this forward rotation. Thus, the upper body and thigh rotate forward, while the lower leg and foot remain fairly stationary. This forward rotation of the upper relative to the lower leg would foster a forward translation of the tibia[6], enhancing the likelihood of ACL rupture.

The discriminant analysis demonstrated that positioning of the body's **COM** is a likely risk factor for ACL-injury, but that it also likely works in conjunction with other factors to cause injury. No control subject landed with the **COM_BOS** greater than 1.6 (Figure 6), thus the position of the trunk relative to the base of support is likely a primary risk factor for ACL-injury when the **COM_BOS** is large. In the range of 1.2-1.6 ACL-injury both occurred and did not occur. In this range the posterior position of the trunk likely combines with other factors in order to result in injury. When the trunk is positioned close to the base of support (**COM_BOS** < 1.2) ACL-injury did not occur, with one exception. In this range the location of the **COM** is not a critical factor and other factors are the most likely cause of injury.

The **COM_BOS** was the measurement of interest for the current study because it provides a more complete description of the dynamic balance stability, as it is the cumulative effect of both lower limb and trunk position. Two previous sagittal-plane studies examined the effect of trunk angle during two-legged drop-landing in healthy controls. These studies concluded that landing with the more extended trunk increased landing and quadriceps forces[4] and increased the anterior shear forces on the tibia[20]. In contrast, a previous study[8], from which the current study evolved, demonstrated that a flexed hip, measured similarly to the afore mentioned trunk angle, was present during a landing maneuver that led to ACL disruption. The divergence in results can be explained by the difference in the task evaluated. In the drop-landing task[4,20] the $limb_G$ angle is quite small, placing the **COM** close to the **BOS**. Thus, trunk extension brings the trunk further from the feet, decreasing stability and increasing the external knee flexor moment. To prevent knee collapse, the quadriceps force is increased. In the provocative position[8], the $limb_G$ angle is large, the hip is flexed, placing the athletes leg anterior to their body, moving the **COM** far posterior to the **BOS**. This likely triggers strong core[35] and quadriceps muscle contraction in response to the unstable posture, which may have a deleterious effect on the ACL.

In a study by Zazulak and colleagues[38] it was demonstrated that athletes who sustain ACL tears have greater pre-injury deficits in proprioceptive repositioning of the trunk compared to uninjured athletes. Due to the small number of individuals that advanced to an ACL-injury (4 females and 2 males) in their prospective study, the role gender played in the relationship of these variables to ACL-injury was not reported. Nonetheless, poor trunk control may have led athletes to allow their **COM** to be positioned in an unstable position posterior to the **BOS**, which contributed to the ACL rupture, irrespective of gender.

As with many imaging studies, an exact measure of the accuracy was not available for the current study. For example, in radiological studies the accuracy is typically assumed to be one half the pixel resolution. On average, the femur length was 37.7 pixels for both populations. The difference in the **COM_BOS** across cohorts was 0.9, which on average would be 32.4 pixels, or 32 times the resolution. If the femur length was again assumed to be 37.5cm, the average resolution was 1 cm. If an accuracy 4 times worse than a radiological study was assumed for the current methods, the accuracy would be 2mm, well below the 38cm reported for the Δ**COM_BOS**. The possible acceptance videos where the athletes were slightly rotated away from the sagittal plane would have added variability into the measures. Yet, even if a "worse-case scenario" was assumed, in which: 1) all the control subjects were rotated 30° away from the sagittal plane, 2) all the injury-videos were captured in a purely sagittal plane, and 3) the scaling by femur_length did not compensate at all for this rotation; the difference in the **COM_BOS** between cohorts dropped to 0.8 and remained significant. Only when the scenario was changed to a 50° angle did the difference between cohorts become insignificant.

There were several potential limitations to this study. The movie clips were collected as a convenience sample and may not be representative of all noncontact ACL-injury mechanisms. Yet, the observed motions likely represented some of the most common noncontact mechanisms of ACL-injury. It was not possible to determine the exact moment at which the ACL-injury occurred, creating possible millisecond differences in the timing of the first sequence picked as the foot touched the ground to the point of injury. However, it was likely that the ACL-injury occurred within 50 msec of ground contact[22]. There were also possible difficulties identifying anatomic landmarks in clothed individuals with no markers, yet the inter- and intra-rater reliability was excellent. Lastly, although every effort was made to eliminate bias throughout the experiment, there remained a minor potential for selection bias, as the inclusion criteria was based on a qualitative analysis. However, the quantitative measurements acquired (with the use of matched controls to reduce these potential errors) were a considerable improvement over previous descriptive studies based purely on visual estimates of body position. The further strengths of the study were the intentional focus on the sagittal plane to explore concepts that were raised in previous 2D sagittal analyses of controls[4,20], eliminating redundancy with previous video-based studies that reported frontal plane kinematics[17], the strong statistical differences between the ACL-injured and control cohorts, and the evaluation of posture during an event that directly resulted in ACL-injury. Lastly, this work represents the largest quantitative video analysis study to date and the only one to match the two cohorts.

In conclusion, athletes captured on video while tearing their ACL landed with the **COM** far posterior to the **BOS**, as compared to controls. This position likely increases the rectus femoris contraction at initial impact in order to prevent a backwards fall. A strong quadriceps contraction lowers the impulse force necessary to tear the ACL, by adding a compressive force as well as a smaller, secondary anterior shear force on the tibia[5,25,34]. Therefore, observation of consistent landing with the **COM** far posterior to the **BOS** may be helpful as a screening test for athletes at risk for noncontact ACL-injury. Future work is needed to determine if training athletes to avoid this dangerous position helps reduce the risk of an ACL-injury.

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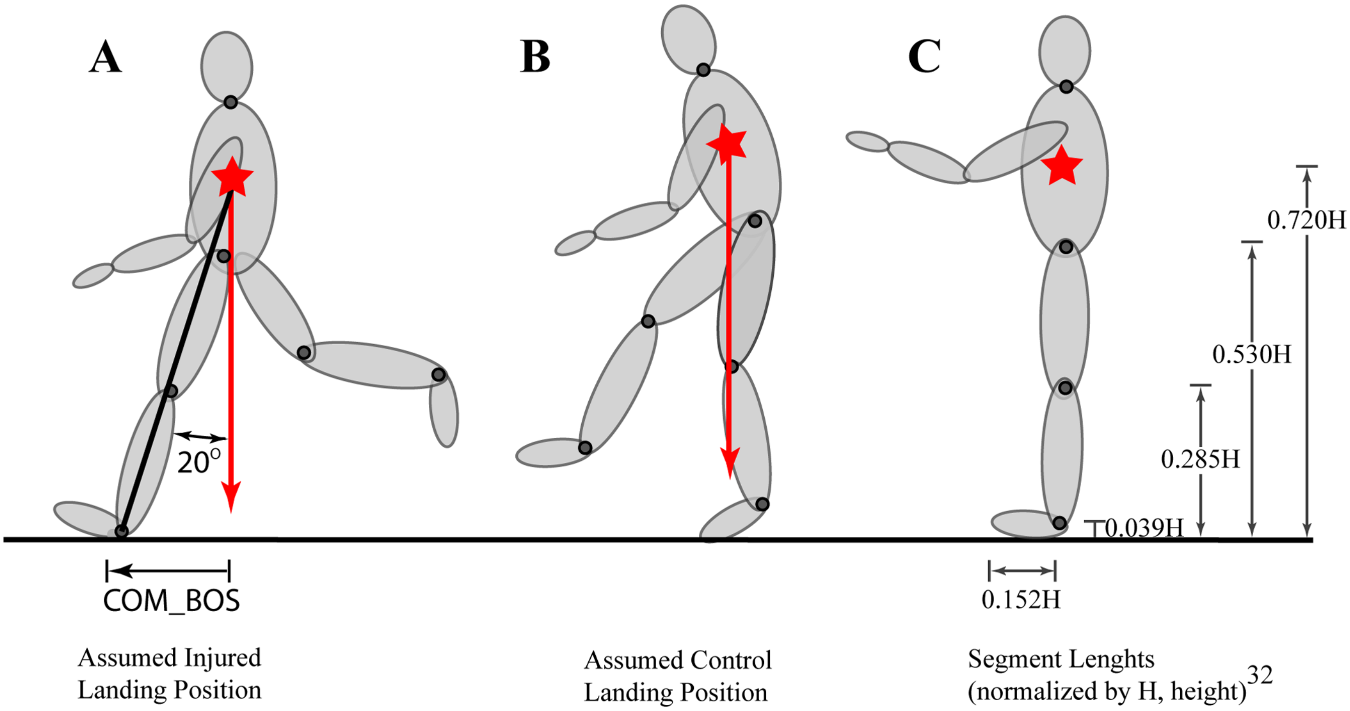

Figure 1. Analysis of Control Landing (left) and landing that was proceeded by an ACL-injury (Right)

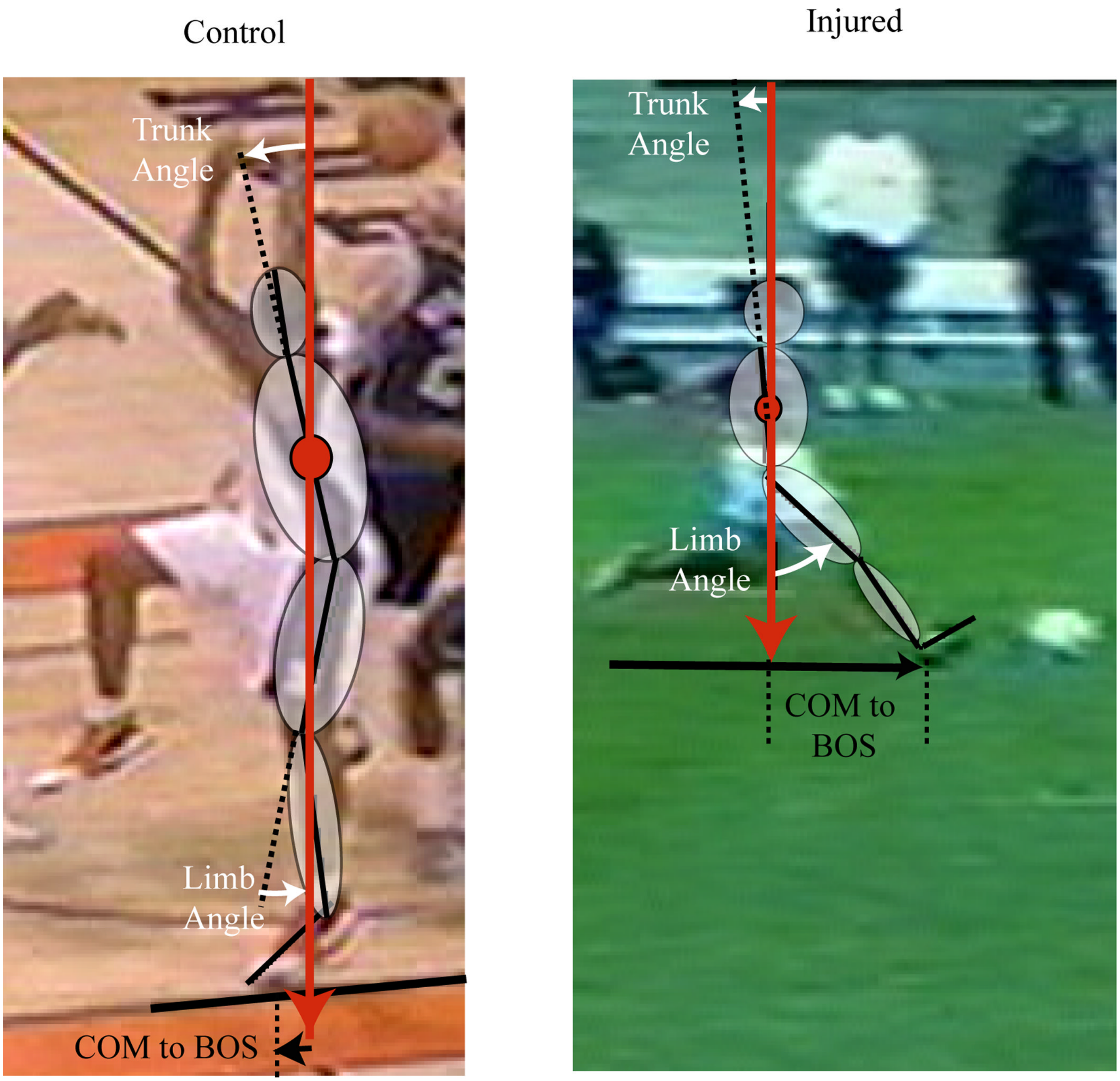

Figure 2. Power Analysis

A: ***Assumed provocative landing position***: In order to perform the power calculations it was assumed that the line between the hip and the heel is 20° from the vertical (gravitational direction). Then the **COM_BOS** was calculated as the distance from the **COM** to the heel of the foot multiplied by the sin of 20° (0.246*H = 0.720*H * sin (20°)). B. ***Assumed safe landing position***: In the control position, it was assumed that that the **COM** was directly over the **BOS**. **C:** ***Segment Lengths:*** Segment lengths normalized by height as provided by Winter[36]. The key measurements used in the current study:

Trunk_to_heel = 0.720H

Femur_length = 0.245H = (0.530H-0.285H)

Foot Length = 0.152H

Foot Length = .0.618*femur_length = 0.152H*(femur_length/0.246H)

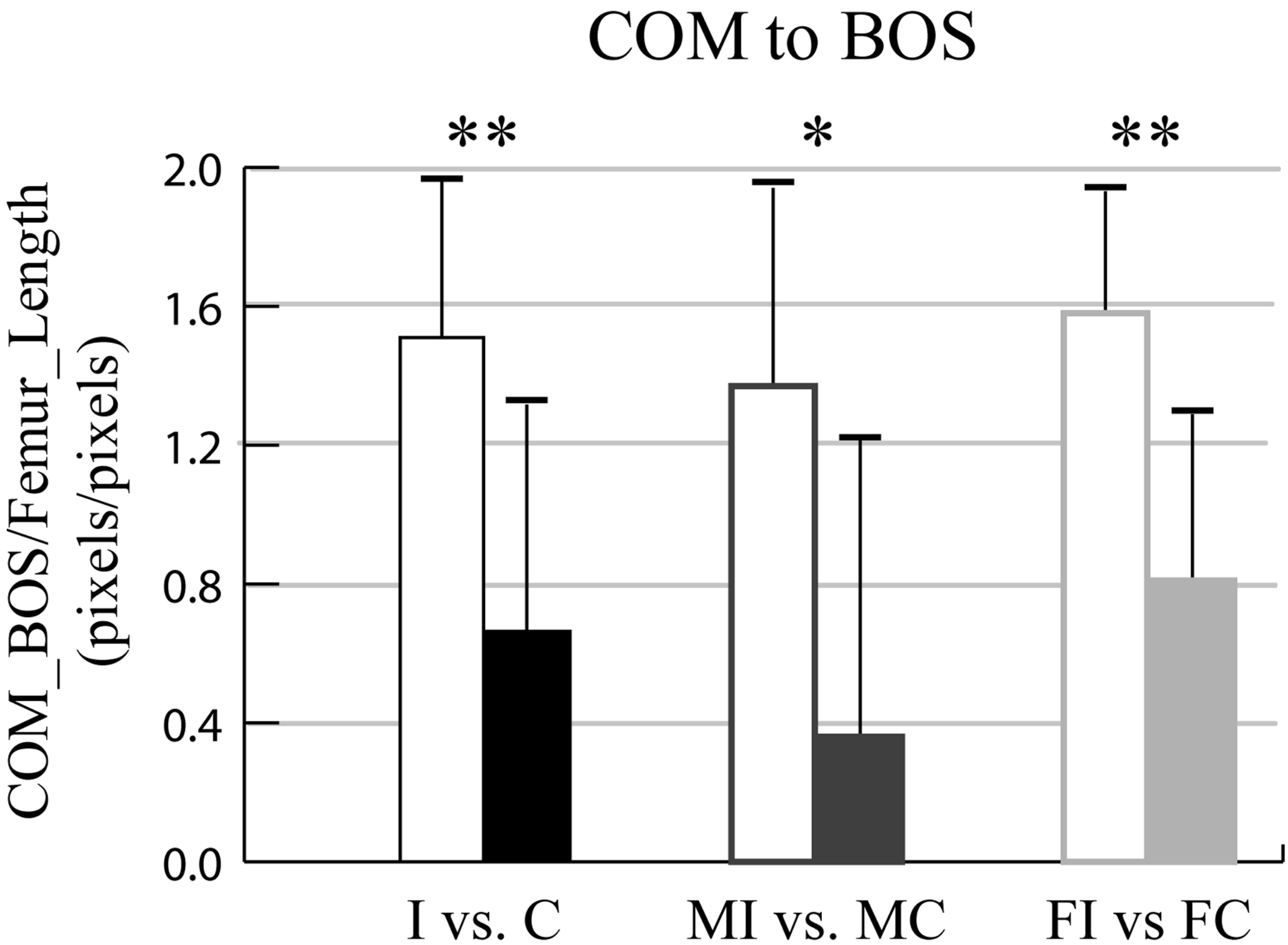

Figure 3. Posterior Displacement of the COM relative to the BOS Normalized by Femur Length

I = injured C= Controls, M = males, F= Females. Injury status was a significant main effect (p<0.001), but gender was not (p=0.080). There were no significant interaction effects (p=0.530).

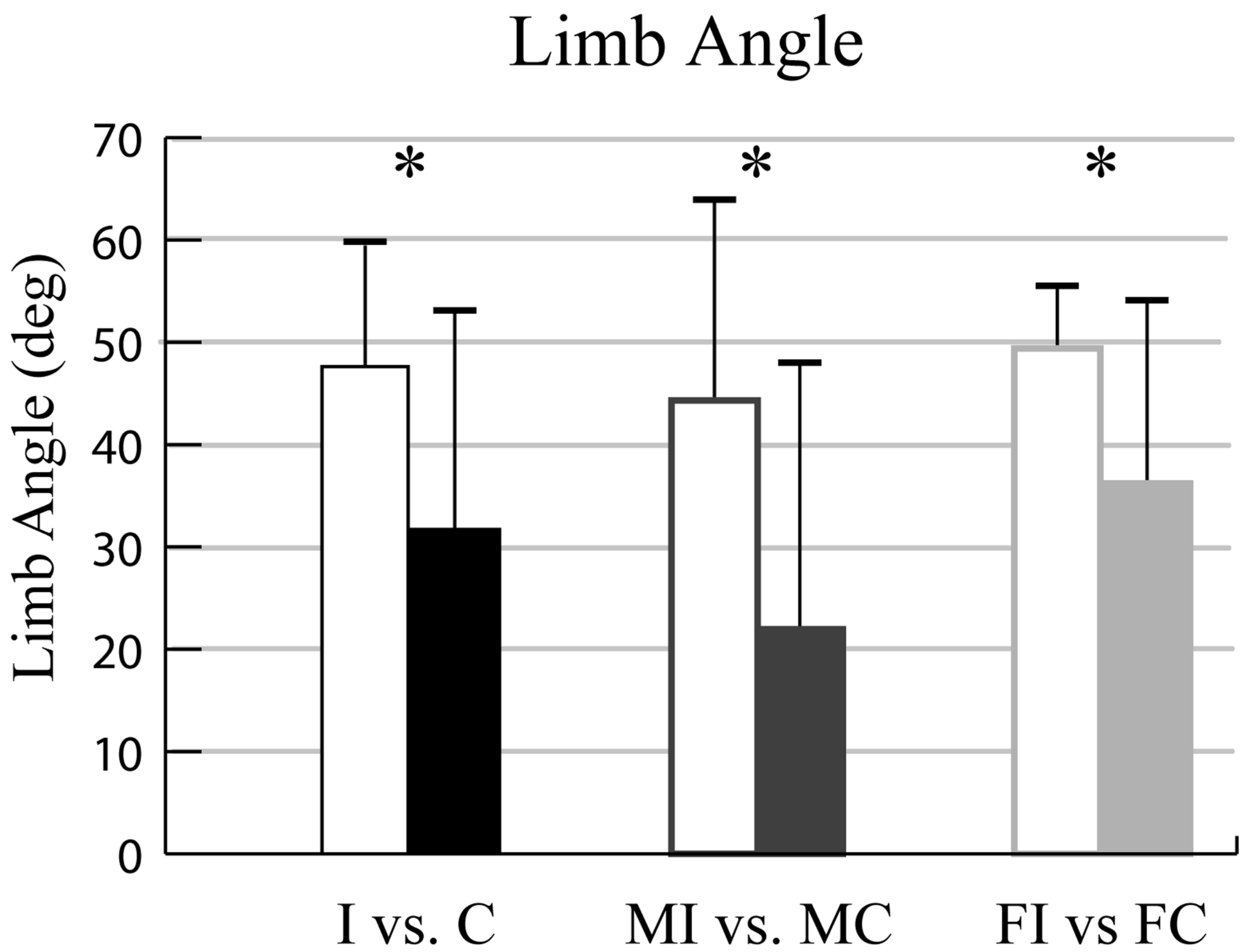

Figure 4. $Limb_G$ relative to the gravitational vector

I = injured C= Controls, M = males, F= Females. Injury status was a significant main effect (p=0.004), but gender was not (p=0.098). There were no significant interaction effects (p=0.425).

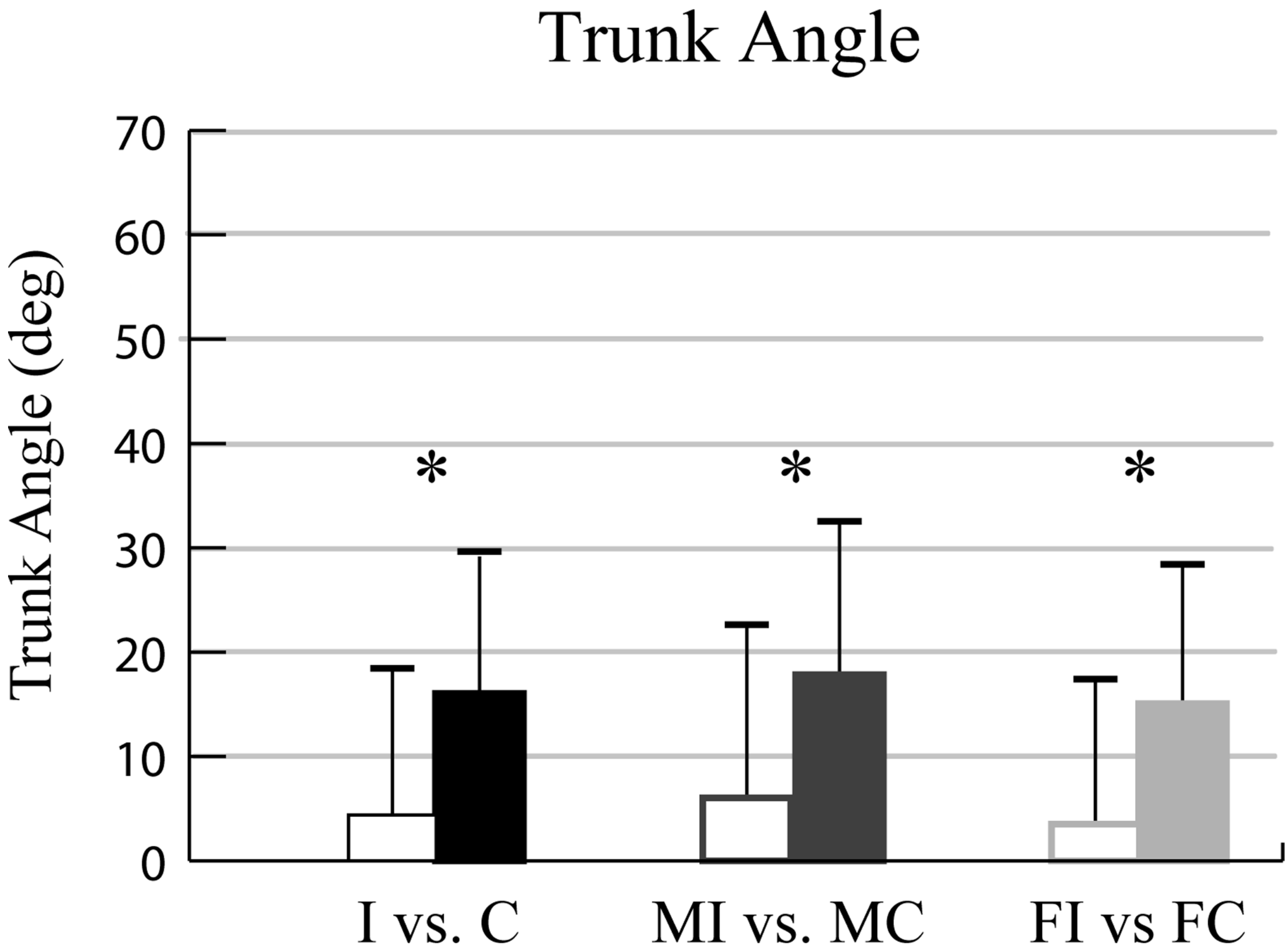

Figure 5. Trunk$_G$ angle relative to the gravitational vector

I = injured C= Controls, M = males, F= Females. Injury status was a significant main effect (p=0.016), but gender was not (p=0.571). There were no significant interaction effects (p=0.980).

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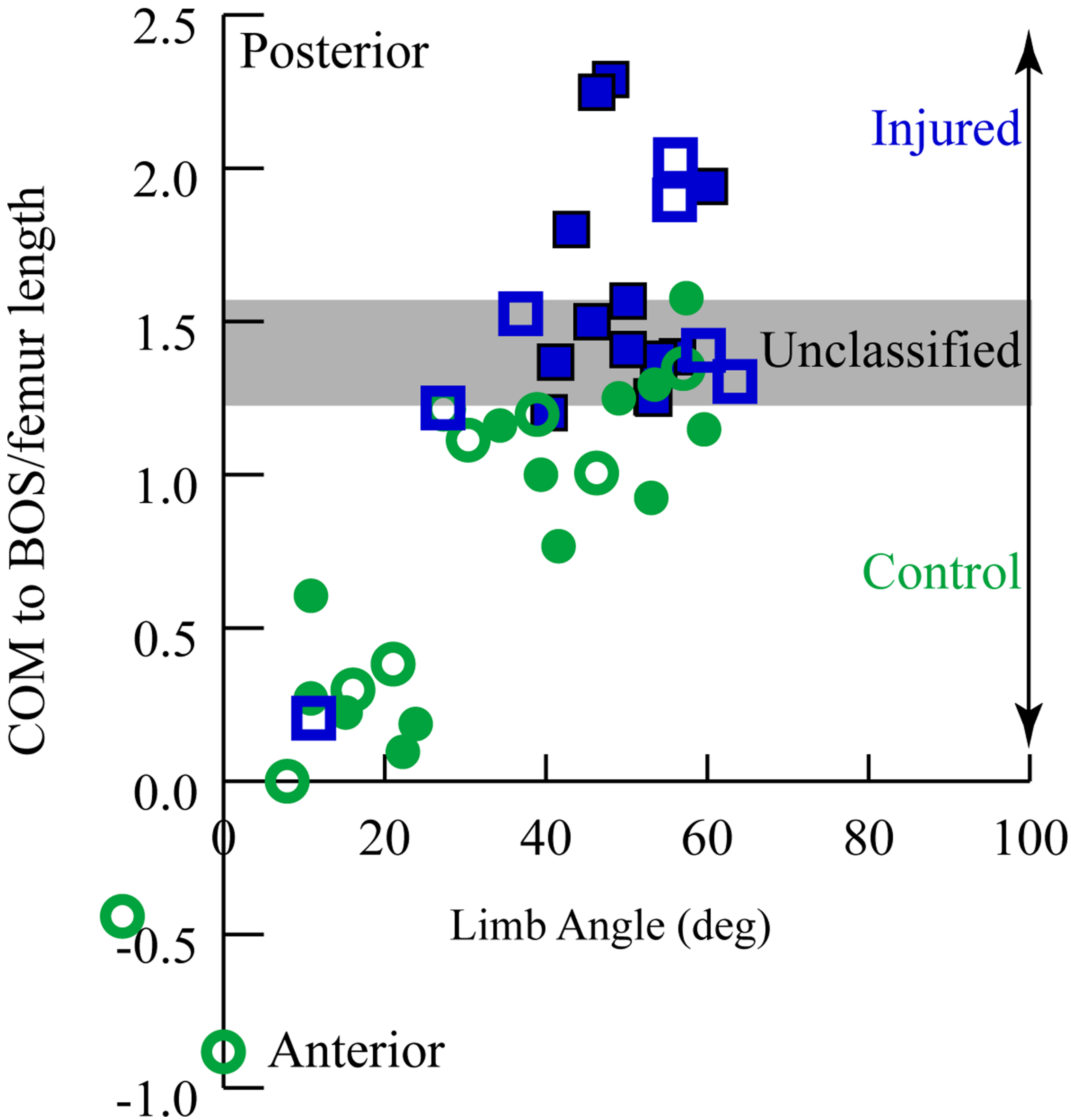

Figure 6. Discriminant Analysis

COM_BOS plotted versus $limb_G$ angle. The data from athletes who sustained an ACL-injury are represented by blue squares. The subjects in the control group are represented by green circles. Hollow symbols represent male subjects and filled symbols represent female subjects. The discriminant analysis determined that **COM_BOS** could predict membership in a group to within 80% accuracy (1 injured case and 7 control cases were misclassified). Neither the $limb_G$ nor the $trunk_G$ angle could discriminate to the same level.

Table 1

Study Participant Descriptions

Differences between the two cohorts were tested using a two-tailed Chi-squared test.

		Injured	Controls	*p*-value
Gender	female	13	13	1.0
	male	7	7	
Sport	basketball	10	10	1.0
	soccer	2	2	
	football	5	5	
	handball	3	3	
Activity just prior to analysis	run-stop	15	17	0.45
	vertical	2	2	
	horizontal jump	3	1	

Table 2

Results

All values are listed as an average ± one standard deviation (SD). The 2×2 design ANOVA indicated that injury_status was a significant factor, but gender was not and there were no interaction effects.

	INJURED			CONTROLS		
	ALL	**Male**	**Female**	**ALL**	**Male**	**Female**
COM_BOS /femur	1.5 ± 0.5	1.4 ± 0.6	1.6 ± 0.4	0.7 ± 0.7	0.4 ± 0.9	0.8 ± 0.5
Limb Angle (deg)	48 ± 12	44 ± 19	49 ± 6	31 ± 22	22 ± 26	36 ± 18
Trunk Angle (deg)	4 ± 14	6 ± 17	4 ± 14	16 ± 13	18 ± 14	15 ± 13