INTRODUCTION

Neuromuscular risk factors likely underlie the higher rate of anterior cruciate ligament (ACL) injuries in female compared to male athletes. Specifically, altered movement patterns, such as dynamic knee abduction (valgus), may increase ACL injury risk in female athletes [1,2]. Increases in these neuromuscular risk factors may coincide with rapid adolescent growth that leads to divergent levels of neuromuscular control between sexes [3]. Hence, the adolescent pubertal growth spurt may be the optimal phase of growth and development to investigate related sex differences in ACL injury risk.

The primary purpose of this study was to determine if the specific timed onset of neuromuscular risk factors related to abnormal movement patterns increased in females, but not males, during the adolescent growth spurt. We hypothesized that during adolescent growth, pubertal females would demonstrate longitudinal increases in knee abduction moments and motion compared to pubertal males. We also hypothesized that following the adolescent growth spurt, post-pubertal females would have significantly greater knee abduction moments and motion compared to post-pubertal males.

METHODS

Using a nested cohort design (total sample = female n=709; male n=250), a subset of 315 subjects met the inclusion criteria for this study (based on 2 consecutive year samples and maturational status). Subjects were classified into two separate maturational groups: pubertal female (PF) n = 145, pubertal male (PM) n = 37, post-pubertal female (PPF) n = 120, post-pubertal male (PPM) n = 13. Each subject participated in two testing sessions approximately one year apart (mean 365.7 ± 14.7 days). Three trials of a drop vertical jump (DVJ) were collected from a 31 cm box. They were instructed to drop directly down off the box and...
immediately perform a maximum vertical jump, raising both arms, jumping for a basketball rebound. 3D knee joint angles were calculated according to the cardan rotation sequence (i.e. flexion/extension, abduction-adduction and internal-external rotation). Kinematic data were combined with force data to calculate knee joint moments using inverse dynamics. Maximum abduction angle and external moments were calculated during the DVJ deceleration phase. Two between group independent variables of sex (female, male) and maturation level (pubertal, post-pubertal), in addition to the within subject independent variable (year 1, year 2), were analyzed in a 2X2X2 ANOVA. An $\alpha \leq 0.05$ was used to indicate statistical significance.

RESULTS AND DISCUSSION
The mean difference in stature between the two testing years was 4.8±2.4 cm in PF and 6.6±2.8 cm in PM compared to 1.0±2.6 cm and 1.6±2.2 cm in PPF and PPM, respectively. This indicates that the pubertal group experienced rapid adolescent growth. There was a significant three-way interaction with peak knee abduction angle ($p=0.029$, Table 1, Figure 1). Post hoc analyses identified a significant longitudinal increase in peak abduction angle in PF ($p<0.001$), but no change in PM ($p=0.90$). PPF had significantly greater overall peak abduction angle following adolescent growth compared to PPM (female -9.3±5.7°; male -3.6±4.6°; $p<0.001$). Peak knee abduction moment increased from the first year to the second year in all subjects (main effect of year $p<0.001$). A two-way interaction between sex and maturation group was identified ($p=0.013$). Post-hoc analysis indicated that PPF had significantly greater peak knee abduction moment compared to PPM (female:-21.9±13.5 Nm; male:-13.0±12.0 Nm; $p=0.017$). Sex differences in knee abduction moment were not observed in pubertal subjects ($p>0.05$). Similar results were found with body-mass normalized knee abduction moments. PPF landed with significantly greater normalized knee abduction moment compared to males (female -0.37 ± 0.23 Nm/kg; male -0.18 ± 0.16 Nm; $p = 0.002$).

CONCLUSIONS
This study identified, through longitudinal analyses, that knee abduction angle was significantly increased in pubertal females during rapid adolescent growth compared to males. In addition, knee abduction motion and moments were significantly greater for consecutive years in young female athletes, following rapid adolescent growth, compared to males. A puberty and sex interaction was found with greater knee abduction moment in PF compared to PPF. In contrast, knee abduction moment was significantly lower in PM compared to PPM. The combination of longitudinal, sex and maturational group differences indicate that early puberty appears to be a critical phase related to the divergence of increased ACL injury risk factors. Injury prevention programs that focus on neuromuscular training may be beneficial to help address the development of ACL injury risk factors that occur in female athletes during maturation.

REFERENCES

ACKNOWLEDGEMENTS
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Table 1: Mean (±SD) peak knee abduction angle and moment for pubertal and post-pubertal subjects.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Test Session</th>
<th>Pubertal</th>
<th>Post-Pubertal</th>
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<tbody>
<tr>
<td>Knee Abduction Angle (deg)</td>
<td>Year 1</td>
<td>Female -7.7 ± 6.1</td>
<td>Male -8.2 ± 5.8</td>
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<tr>
<td></td>
<td></td>
<td>Female -9.3 ± 6.2</td>
<td>Male -8.3 ± 6.2</td>
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<tr>
<td>Knee Abduction Moment (Nm)</td>
<td>Year 1</td>
<td>Female -14.4 ± 10.9</td>
<td>Male -16.4 ± 12.3</td>
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<tr>
<td></td>
<td></td>
<td>Female -19.2 ± 12.1</td>
<td>Male -19.4 ± 15.0</td>
</tr>
</tbody>
</table>

$^a$Denotes interaction of year, sex, maturation, $^b$Denotes interaction of sex and maturation. ($p<0.05$)