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Original research

Effects of maturation on combined female muscle strength and ACL structural factors

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ABSTRACT

Objectives: Relations between lower limb muscle strength and female ACL injury risk are well documented. How these relations combine with key ACL geometries however, is unknown. Identifying how these combined factors are impacted by maturation would benefit current risk screening and prevention efforts. This study compared hamstrings and quadriceps strength and ACL cross sectional area (CSA) indices across three maturation groups.
Design: Cross-sectional human experimental.
Methods: MRI scans of the dominant knee were collected in 35 females stratified into early (9.7 ± 0.8 yrs), middle (12.9 ± 1.7 yrs), and late (14.8 ± 0.6 yrs) maturation groups. Hamstring and quadriceps muscle volumes and ACL CSA measures were obtained. Isokinetic strength data were quantified for dominant knee flexors and extensors. Peak hamstring and quadriceps concentric and eccentric strength per unit volume magnitudes (QCSPV, HCSPV, QESPV, HESPV) were determined. Metrics and select ratios were submitted to a one way ANOVA to determine the main effect of maturation.
Results: Significant decreases occurred in HESPV (N/cm^3) and ACL CSA ($cm^2/kg\,m$), respectively, from early ($0.188 \pm 0.023\ N/cm^3$, $0.007 \pm 0.002\ cm^2/kg\,m$) to middle ($0.157 \pm 0.029\ N/cm^3$, $0.005 \pm 0.002\ cm^2/kg\,m$, $p = 0.034$, $p = 0.029$), and middle to late ($0.132 \pm 0.031\ N/cm^3$, $0.003 \pm 0.001\ cm^2/kg\,m$, $p = 0.044$, $p = 0.018$) maturation. A significant decrease in HESPV:QCSPV occurred between early (1.795 ± 0.496) and middle (1.362 ± 0.277, $p = 0.018$) maturation. QCSPV:ACL CSA was significantly greater in late (37.26 ± 13.35) compared to middle (25.81 ± 9.17, $p = 0.021$) maturation.
Conclusions: Key ratios between female knee quadriceps and hamstring strength and ACL size parameters, which may directly impact ACL injury risk, are substantially different among three maturation states. The results are potentially hazardous strength mismatches in mid-pubertal females, where a smaller (weaker) ACL may be unable to stabilize quadriceps dominated loading strategies.

1. Introduction

Despite the increased quantity[1] and enhanced quality[2] of anterior cruciate ligament (ACL) injury prevention programs, injury rates and their associated sex disparity have endured.[3] This limitation stems primarily from an incomplete understanding of the multi-factorial nature of ACL injury mechanisms. Furthermore, the optimal time point to first introduce a prevention strategy remains largely unknown, compromising its effectiveness in countering underlying risk factors. Determining when certain high-risk morpho-mechanical combinations occur can provide an important baseline to successfully redirect injury trends.

For dynamic landings in which ACL injury is common, the large 3-D inter-segmental loads arising at ground impact are necessarily restrained by muscle-tendon loading across the joint in combination with internal passive joint structures.[4] The relative strengths of quadriceps and hamstring muscle groups, which contribute substantially to dynamic knee stabilization during high impact scenarios,[5] are thus critical. Strength imbalances between the quadriceps and hamstrings muscle groups are often touted as an important predictor of ACL injury risk, particularly in females.[6] Specifically, comparatively weak hamstrings are deemed to promote excessive and potentially debilitative quadriceps-induced anterior tibial shear loads during landings.[7,8] The net result is a volatile internal joint loading scenario that cannot be adequately countered by passive ACL restraint.[7]

While hamstring–quadriceps muscle strength ratio contributions to ACL injury have been studied extensively,[5,9] few have

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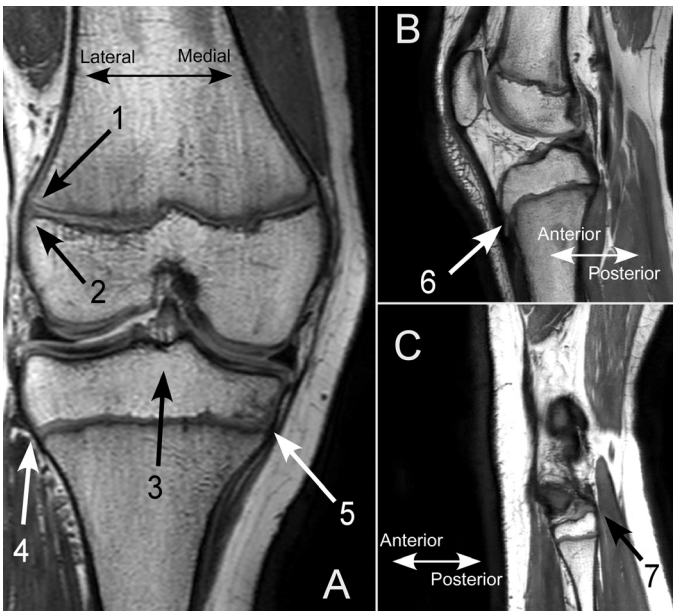

Fig. 1. Tibial, femoral, and fibular epiphyseal plate indicators used to determine maturation stage: (1) proximal projection of lateral corner of distal femoral epiphysis (A), (2) lateral metaphyseal capping of distal femoral epiphysis (A), (3) formation of tubercles on tibial plateau (A), (4) distal projection of lateral corner of proximal tibial epiphysis (A), (5) distal projection of medial corner of proximal tibial epiphysis (A), (6) development of tibial tuberosity (B), (7) development of fibular styloid process (C).

extended analyses to consider the comparative characteristics of the ACL. A quadriceps dominant strength imbalance, for example, may be less hazardous when combined with a stronger ACL. Conversely, injury risk may be greater when any level of strength imbalance presents with a weaker ligament. Reliable ACL strength estimates currently exist in literature[10] but are virtually impossible to obtain in-vivo. Strong positive associations exist, however, between ACL cross-sectional area (CSA) and ACL ultimate failure load.[11] If a quadriceps dominant muscle strength imbalance is indeed an ACL injury risk factor, then extending analyses to consider the comparative size of the ACL may be beneficial.

A large number of knee joint disorders, including ACL injury, do not present with high incidence until after maturation onset.[12] The sex-based disparity evident in adolescent ACL injury rates similarly does not exist prior to the developmental growth spurt.[13] Sports relevant lower limb joint biomechanics demonstrate noticeable maturation dependence, with high-risk profiles being more frequent in females by the middle stages of puberty[14]. The adolescent growth spurt represents a time when changes in body size and composition and associated loading phenomena precipitate substantial osteogenic and morphologic adaptation.[15–17] Relative changes in combined quadriceps and hamstring size and strength and ACL geometric indices across maturation may thus impact resultant ACL injury potential.

It is currently unclear how hamstring to quadriceps strength ratios and associated ACL cross sectional area compare at explicit time points across maturation. Establishing these relations and additionally determining when high-risk combinations first appear will immediately enhance ACL injury risk screening and prevention efforts, particularly regarding their foci and timing. With this in mind, we aimed to compare the strength per unit volume (SPV) of the quadriceps and hamstrings muscles to ACL CSA across three distinct maturation groups. With female ACL injury rates spiking during the adolescent growth spurt,[14,17] we hypothesized that 'worst case' combinations of these factors would present during this critical mid-maturation period.

2. Methods

Thirty-five healthy, recreationally active maturing females (13.4 ± 3.2 yrs) were recruited to participate in this cross-sectional study design. They were stratified into three maturation groups early ($n = 9$, age: 9.7 ± 0.8 yrs, Wt: 29.48 ± 4.13 kg, Ht: 1.34 ± 0.10 m), middle ($n = 15$, age: 12.9 ± 1.7 yrs, Wt: 39.90 ± 8.03 kg, Ht: 1.51 ± 0.11 m), and late ($n = 11$, age: 14.8 ± 0.6 yrs, Wt: 53.43 ± 3.93 kg, Ht: 1.67 ± 0.04 m) based on a series of pre-defined knee joint anatomical factors.[18] Groups of this size were estimated to detect statistically significant ($p = 0.05$) between-group differences in our pre-defined muscle strength[9] and ACL CSA factors[11] with 80% power. Participant exclusion criteria for this study were: (1) history of previous knee injury or surgery, (2) pain in lower extremity prior to testing, or (3) history of knee fracture or extreme immobilization. Prior to testing, University Institutional Review Board approval and written participant informed consent was obtained.

Maturation group was determined based on the presence of explicit nonmetric dominant limb (knee) epiphyseal maturity indicators,[19] quantified within a series of high-resolution multi-planar magnetic resonance (MR) images (Achieva 3.0 Tesla system-Philips Medical Systems, Eindhoven, Netherlands). Seven

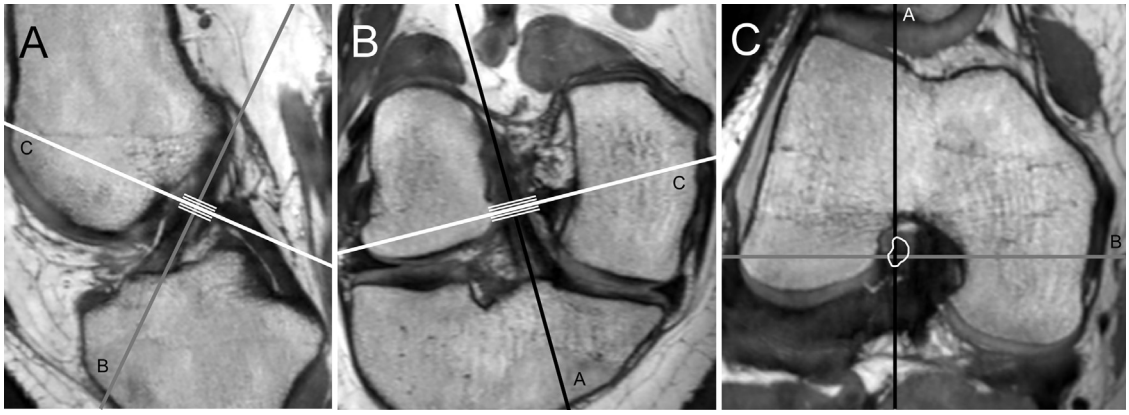

Fig. 2. Example measurement of ACL CSA. MR images were resampled along the longitudinal axis of the ACL to provide two parallel (A and B) and one perpendicular (C) views. The ACL CSA was outlined in the perpendicular slice. Five total perpendicular slices were averaged together to determine ACL CSA at the midpoint. Abbreviations: CSA, cross-sectional area; MR, magnetic resonance.