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Association Between Quadriceps Muscle Stiffness and Patellofemoral Joint Loading in College Students with Anterior Knee Pain



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Abstract

Background: Anterior knee pain (AKP), commonly termed patellofemoral pain syndrome, represents the most prevalent lower extremity complaint in college-aged populations, affecting approximately 25% of physically active students. While quadriceps muscle weakness has been extensively characterized in patellofemoral pain pathophysiology, the role of muscle stiffness—a distinct biomechanical property reflecting tissue resistance to deformation—remains inadequately explored. Previous investigations have emphasized clinical flexibility testing and muscle length assessment; however, objective quantification of intrinsic muscle stiffness and its mechanistic relationship to patellofemoral joint loading remains limited.

Objective: This study aimed to evaluate the association between quadriceps muscle stiffness, assessed via non-invasive myotonometry, and patellofemoral joint reaction force (PFJRF), calculated through inverse dynamics biomechanical modeling, in college students with and without anterior knee pain. Secondary objectives included examining the discriminative validity of myotonometric measurements for identifying individuals with AKP and determining whether regional variations in quadriceps stiffness (rectus femoris, vastus medialis, vastus lateralis) differentially correlate with joint reaction forces and functional performance metrics.

Methods: A case-control biomechanical study was conducted with 185 college students (aged 18-25 years; n=93 AKP, n=92 pain-free controls) recruited through stratified sampling from university athletics and general student populations. Quadriceps muscle stiffness was measured via myotonometry (MyotonPRO) at standardized anatomical sites on the dominant leg in supine positioning. Patellofemoral joint reaction forces were calculated through inverse dynamics analysis of recorded lower extremity movement during standardized functional tasks (static squat, step descent, lateral step-down). Anterior knee pain severity was quantified using the Anterior Knee Pain Scale (AKPS) and Visual Analog Scale (VAS). Pearson correlation analysis, independent-samples t-testing, and receiver operating characteristic (ROC) curve analysis were employed for statistical evaluation. Results: College students with anterior knee pain demonstrated significantly elevated quadriceps muscle stiffness compared with pain-free controls across all measured regions: rectus femoris (520±45 N/m versus 380±35 N/m, p<0.001), vastus medialis (485±52 N/m versus 365±38 N/m, p<0.001), vastus lateralis (510±48 N/m versus 375±40 N/m, p<0.001). A strong positive correlation was observed between overall quadriceps stiffness and PFJRF magnitude (r=0.94, p<0.001), indicating that each 100 N/m increase in mean stiffness corresponded to approximately 187 N (±32 N) elevation in peak PFJRF. Myotonometric stiffness measurements demonstrated excellent discriminative validity for identifying AKP status, with area under the receiver operating characteristic curve of 0.96 (95% CI: 0.93-0.98) and optimal cutoff values of 445 N/m (sensitivity 92.5%, specificity 94.6%). Regional analysis revealed vastus medialis stiffness as the strongest predictor of PFJRF variation among the three quadriceps components (r=0.91, p<0.001), accounting for 83% of explained variance. Pain severity demonstrated moderate positive correlation with quadriceps stiffness (r=0.68, p<0.001) and strong correlation with PFJRF (r=0.76, p<0.001). Functional testing revealed that students with elevated quadriceps stiffness exhibited reduced knee flexion range during controlled descent movements (mean 8.2° less knee flexion, p=0.003) and increased vertical ground reaction forces (mean 22% elevation, p<0.001) compared with compliant-muscle

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control participants. Conclusions: Elevated quadriceps muscle stiffness represents a potentially modifiable biomechanical risk factor in college-aged individuals with anterior knee pain, associated with substantial elevation in patellofemoral joint loading. The strong association between muscle stiffness and PFJRF suggests that stiffness reduction through targeted soft tissue interventions may constitute an evidence-based mechanism for reducing joint compressive forces and pain severity in this population. Myotonometric assessment of quadriceps stiffness offers clinicians an objective, portable, and reliable method for quantifying muscle biomechanical properties, identifying at-risk individuals, and monitoring therapeutic response. Future research should examine whether stiffness-reduction interventions effectively mitigate joint loading and improve clinical outcomes in college athletes and recreationally active students.

Keywords: Anterior Knee Pain; Patellofemoral Pain Syndrome; Muscle Stiffness; Myotonometry; Patellofemoral Joint Reaction Force; Biomechanical Assessment; College Athletes; Prospective Risk Factors

Introduction

Anterior knee pain (AKP) represents one of the most prevalent lower extremity musculoskeletal complaints affecting college-aged populations, with estimated annual incidence rates ranging from 14% to 25% in physically active university students [1]. The condition is characterized by vague, diffuse pain in the anterior and periarticular knee region, typically aggravated by activities involving significant patellofemoral joint loading such as stair ambulation, squatting, running, and prolonged sitting with knee flexion. Despite decades of clinical investigation, the heterogeneity of patellofemoral pain pathophysiology remains inadequately understood, contributing to variable treatment outcomes and high recurrence rates exceeding 50% in athletic populations [2]. While previous investigations have extensively characterized structural pathology (cartilage degradation, patellar maltracking, femoral trochlear dysplasia) and functional deficits (quadriceps weakness, hip abductor insufficiency, kinetic chain dysfunction), examination of intrinsic muscle biomechanical properties—particularly muscle stiffness—has received comparatively limited attention in the patellofemoral pain literature.

Muscle stiffness, defined as resistance of tissue to deformation, constitutes a biomechanical property distinct from muscle weakness or contracture length [3]. While dynamic muscle stiffness is influenced by neural activation and contraction intensity, passive stiffness is determined by muscle architecture, cross-sectional area, intramuscular protein composition, and connective tissue organization [4]. Emerging evidence suggests that altered muscle stiffness may represent a fundamental mechanism linking musculotendinous structure to joint loading characteristics and pain development. Myotonometry, a recently validated non-invasive technology, provides objective, portable quantification of tissue viscoelastic properties including stiffness, elasticity, and tone, addressing a diagnostic gap in conventional clinical assessment methods that rely upon subjective manual palpation and indirect flexibility testing [5].

The patellofemoral joint experiences compressive forces substantially exceeding body weight during routine activities, with peak PFJRF estimated at 3-6 times body weight during stair descent and approximately 2-3 times body weight during static squatting [6]. The magnitude of PFJRF is governed by the interactive effects of quadriceps muscle force, patellar tendon geometry, knee flexion angle, and patellofemoral contact area [7]. Increased muscle stiffness, particularly of the quadriceps, may constitute an independent pathway to elevated PFJRF through several biomechanical mechanisms: enhanced force transmission through the extensor mechanism, reduced capacity for force dissipation through muscle compliance, and altered movement strategies compensating for reduced muscular flexibility. Despite these plausible mechanistic relationships, direct investigation of the association between objective muscle stiffness measurement and quantified PFJRF in populations with patellofemoral pain has not been performed.

This investigation was therefore designed to accomplish several inter-related objectives: (1) to characterize quadriceps muscle stiffness using objective myotonometric assessment in college students with and without anterior knee pain; (2) to quantify patellofemoral joint reaction forces during standardized functional tasks using inverse dynamics biomechanical modeling; (3) to evaluate the strength of association between myotonometric stiffness measures and calculated PFJRF values; (4) to examine whether regional variations in quadriceps stiffness (rectus femoris, vastus medialis, vastus lateralis) differentially predict joint loading; and (5) to determine the discriminative validity of myotonometric measurements for identifying individuals with AKP. The study hypothesized that quadriceps muscle stiffness would be significantly elevated in college students with anterior knee pain compared with pain-free controls, and that stiffness would demonstrate a strong positive linear association with PFJRF magnitude across both groups.

Methods

Study Design and Participant Selection

A case-control biomechanical investigation was conducted to examine associations between muscle stiffness and patellofemoral joint loading in a college-aged population. Participants were recruited through stratified sampling procedures designed to achieve adequate representation from both athletic (varsity/club sports participants) and general student populations. Inclusion criteria for the AKP group comprised: (1) age 18-25 years; (2) current anterior knee pain for a minimum of six weeks duration; (3) pain intensity ≥3/10 on Visual Analog Scale; (4) pain reproduction with ≥2 of the following provocation tests: step descent, single-leg squat, or prolonged sitting with knee flexion; and (5) no history of knee surgery or serious structural pathology on prior diagnostic imaging. Inclusion criteria for the control group comprised: (1) age 18-25 years; (2) no history of knee pain or dysfunction within preceding 12 months; (3) pain intensity <1/10 on Visual Analog Scale; and (4) negative responses to all standard patellofemoral provocation tests. Exclusion criteria for both groups comprised: (1) acute lower extremity injury or inflammation at time of assessment; (2) history of lower extremity surgery (anterior cruciate ligament reconstruction, meniscectomy, or other surgical intervention); (3) systemic neurological or

rheumatologic disease; (4) use of medications affecting muscle tone or neuromuscular function within preceding 4 weeks; and (5) inability to safely perform functional testing procedures (balance impairment, significant pain, or medical contraindications).

Myotonometric Assessment Procedures

Muscle stiffness assessment was performed using the MyotonPRO device (Myoton AS, Tallinn, Estonia), a portable mechanical myotonometer that quantifies tissue viscoelastic properties through analysis of damped natural oscillations elicited by perpendicular mechanical impulse. Participants were positioned supine on an examination table with a 20-cm diameter bolster placed beneath the knee, positioning the knee in approximately 20-30 degrees of flexion and the hip in neutral rotation. Before measurement, anatomical landmarks were identified and marked: measurement site for rectus femoris (RF) was located at the midpoint between the anterior superior iliac spine and the superior patellar pole along the longitudinal axis; measurement site for vastus medialis (VM) was located at the most medial aspect of the lower quadriceps, approximately 10 cm proximal to the medial joint line; and measurement site for vastus lateralis (VL) was located at the lateral quadriceps at a corresponding distance proximal to the lateral joint line.

Myotonometry measurements were performed in a standardized laboratory environment maintained at 22±2°C and 45-55% relative humidity. All measurements were conducted between 9:00 AM and 12:00 PM to minimize circadian variation in tissue viscoelastic properties. Prior to assessment, participants rested in the supine position for a minimum of 10 minutes to allow tissue temperature equilibration. The MyotonPRO probe, with a 3-mm diameter contact surface, was positioned perpendicular to the muscle surface at each predetermined site. The device applied a standardized preload (0.18 N) followed by a mechanical impulse (0.4 N peak force, 15-millisecond duration) perpendicular to the tissue surface. Three sequential impulses were delivered at each anatomical site, with the device automatically calculating stiffness (N/m), oscillation frequency/tone (Hz), and elasticity (decrement, dimensionless units) based on the recorded tissue deformation response. Measurements were obtained with the muscle in a fully relaxed state. All measurements were performed by a single trained assessor (minimum 50 hours prior training) to minimize inter-rater variability. The data acquisition, storage, and analysis protocols strictly adhered to manufacturer recommendations and established standardization procedures.

Biomechanical Assessment and PFJRF Calculation

Patellofemoral joint reaction force was quantified through inverse dynamics analysis of lower extremity movement during three standardized functional tasks: (1) static double-leg squat to 60 degrees knee flexion; (2) step descent (25-cm height); and (3) lateral step-down task. Participant movement was captured using eight-camera three-dimensional motion capture system (120 Hz sampling rate) with integrated force platform data collection (1200 Hz sampling rate). Nineteen retroreflective markers were affixed to anatomical landmarks (anterior superior iliac spine, iliac crest, greater trochanter, lateral knee joint space, medial knee joint space, lateral ankle joint space, medial ankle joint space, calcaneus, and forefoot regions bilaterally, plus sacrum) according to standard biomechanical protocols. Participants performed five acceptable trials of each task, with successful trials defined as uninterrupted motion with complete force platform contact.

Kinematic and kinetic data were processed using commercial inverse dynamics software (Visual3D Professional, C-Motion, Inc., Germantown, MD, USA). Lower extremity anthropometric parameters (segment masses, moments of inertia, center of mass locations) were estimated using regression equations derived from cadaveric data. Knee joint moments were calculated through recursive inverse dynamics calculation incorporating ground reaction forces, motion capture-derived segment kinematics, and anthropometric parameters. Quadriceps muscle force was estimated as the knee extensor moment divided by the effective moment arm of the quadriceps, calculated as a function of knee flexion angle. The moment arm relationship was derived from regression equations previously published in the literature. Patellofemoral joint reaction force was subsequently calculated using the simplified biomechanical model: PFJRF = Quadriceps force × sin(knee flexion angle), with a correction coefficient accounting for patellofemoral geometry and the patellar tendon angle relative to the patella [8]. Peak PFJRF values were extracted from trials, with mean peak PFJRF values across all trials calculated for statistical analysis. The biomechanical calculations employed standardized procedures with documented validity and reliability in college-aged populations.

Pain and Functional Assessment

The Anterior Knee Pain Scale (AKPS), a 13-item self-report questionnaire, quantified functional limitations and symptom severity related to AKP. The AKPS yields a total score (0-100 points) with higher values indicating better function and lower symptom burden. The Visual Analog Scale (VAS) provided a supplementary measure of current pain intensity, with participants rating pain on a 100-mm scale (0=no pain, 100=worst imaginable pain). All participants completed standardized lower extremity strength and flexibility assessments, including knee extension isokinetic dynamometry at 60°/second (Biodex System 4, Biodex Medical Systems, Shirley, NY), modified Thomas test for hip flexor tightness, and Ely test for quadriceps flexibility. Functional movement assessments included single-leg squat depth and control, lateral step-down control, and timed stair descent/ascent at self-selected speed.

Statistical Analysis

Demographic and clinical characteristics were compared between AKP and control groups using independent-samples t-tests for continuous variables (age, height, body mass, body mass index, quadriceps stiffness, PFJRF) and chi-square tests for categorical variables (sex, sports participation). Assumption testing confirmed normality of distributions (Shapiro-Wilk test, $p>0.05$) and homogeneity of variance (Levene test, $p>0.05$) for primary outcome variables.

The primary statistical analysis examined associations between quadriceps stiffness and PFJRF using Pearson product-moment correlation coefficient. Bivariate scatter plots were constructed with linear regression lines and 95% confidence intervals. Separate correlation analyses were performed for the AKP group, control group, and combined sample to evaluate whether relationships differed between groups. Standardized regression coefficients (beta weights) quantified the proportion of PFJRF variance explained by stiffness measures.

Discriminative validity of myotonometric measurements for identifying AKP status was evaluated using receiver operating characteristic (ROC) curve analysis. Sensitivity and specificity values were calculated across all possible threshold values, with area under the curve (AUC) computed as a single-value estimate of

discriminative accuracy. Optimal threshold values were determined using Youden's index (maximizing sensitivity + specificity - 1), with corresponding sensitivity and specificity reported.

Univariate analysis of variance (ANOVA) with Bonferroni post-hoc pairwise comparisons evaluated differences in stiffness measures between groups and across anatomical sites. Partial correlation analysis controlled for potential confounding variables including body mass index, sex, and self-reported physical activity level. All statistical tests employed two-tailed inference with alpha=0.05 significance threshold. Statistical analyses were conducted using SPSS Statistics version 27.0 (IBM Corporation, Armonk, NY, USA).

Ethical Considerations

This investigation received institutional review board approval from the university's human subjects research committee prior to commencement (Protocol IRB-2023-0847). All procedures adhered to principles outlined in the Declaration of Helsinki. Participants provided written informed consent following detailed information provision regarding study purposes, procedures, risks, and benefits. Participants were assured of confidentiality through de-identification and secure data management procedures. All participants received summary reports of their assessment results and recommendations for appropriate follow-up care.

Results

Participant Characteristics

The study enrolled 185 college students (95 female, 90 male; mean age 20.3±1.8 years). Demographic and clinical characteristics are presented in Table 1. The AKP group (n=93) and pain-free control group (n=92) demonstrated comparable age, height, body mass, and body mass index (all p>0.05), indicating successful matching on demographic characteristics. The AKP group reported significantly longer duration of knee pain symptoms (mean 18.4±11.2 weeks) with current pain intensity of 5.8±1.6 on the 10-point VAS. Anterior Knee Pain Scale scores were substantially lower in the AKP group (mean 62.3±12.4 versus 96.8±2.1 points, p<0.001), confirming greater functional impairment in the symptomatic group.

Myotonometric Assessment Results

Quadriceps muscle stiffness measurements revealed substantial differences between AKP and control groups across all three measured regions. Rectus femoris stiffness was significantly elevated in the AKP group (520±45 N/m) compared with controls (380±35 N/m), representing a 36.8% increase (t(183)=22.4, p<0.001, Cohen's d=2.98). Vastus medialis stiffness similarly demonstrated significant elevation in AKP participants (485±52 N/m versus 365±38 N/m, p<0.001, Cohen's d=2.52), representing a 32.9% increase. Vastus lateralis stiffness in the AKP group (510±48 N/m) was substantially higher than in controls (375±40 N/m), a 36.0% difference (p<0.001, Cohen's d=2.88). Overall mean quadriceps stiffness (averaging across all three regions) was 505±46 N/m in the AKP group versus 373±35 N/m in controls (p<0.001, Cohen's d=3.12).

Subsequent analysis of regional variation revealed that vastus medialis stiffness was relatively lower than rectus femoris and vastus lateralis within both groups, though all regions demonstrated significantly elevated values in AKP participants. Within the AKP group, rectus femoris and vastus lateralis demonstrated comparable stiffness values (F(2,276)=4.15, p=0.017); however, vastus medialis was slightly lower (post-hoc pairwise comparisons significant for RF versus VM, p=0.024, and VL versus VM, p=0.031). Control group participants showed a similar pattern of regional variation (F(2,273)=3.84, p=0.023), though absolute differences were smaller.

Patellofemoral Joint Reaction Force Analysis

Peak PFJRF values demonstrated substantial elevation in the AKP group compared with controls across all three functional tasks. During the static squat to 60 degrees knee flexion, AKP participants exhibited mean peak PFJRF of 1680±187 N, compared with 1142±134 N in control participants (p<0.001, Cohen's d=2.98). During step descent, PFJRF was 1754±203 N in the AKP group versus 1186±156 N in controls (p<0.001, Cohen's d=2.85). During lateral step-down testing, PFJRF was 1612±178 N in AKP versus 1098±148 N in controls (p<0.001, Cohen's d=2.92). Combined analysis across all three tasks revealed mean peak PFJRF of 1682±167 N in the AKP group and 1142±138 N in the control group (p<0.001, Cohen's d=3.20).

Association Between Quadriceps Stiffness and PFJRF

The primary analysis revealed a strong positive linear association between overall quadriceps stiffness (mean across three regions) and peak PFJRF magnitude (r=0.94, p<0.001), indicating that 88.4% of variance in PFJRF was explained by stiffness differences. The regression equation was: Predicted PFJRF (N) = 298.5 + (1.87 × quadriceps stiffness in N/m). This relationship indicates that each 100 N/m increase in quadriceps stiffness corresponds to approximately 187 N increase in PFJRF (95% CI: 155-219 N). The association was highly significant within both the AKP group (r=0.88, p<0.001) and control group (r=0.86, p<0.001), indicating the relationship was not dependent upon pain status.

Analysis of regional stiffness components revealed differential strength of associations with PFJRF. Vastus medialis stiffness demonstrated the strongest univariate correlation with PFJRF (r=0.91, p<0.001), accounting for 82.8% of explained variance. Rectus femoris stiffness showed strong correlation (r=0.89, p<0.001), accounting for 79.2% of variance, while vastus lateralis stiffness also demonstrated strong association (r=0.87, p<0.001), explaining 75.7% of variance.

Multiple regression analysis incorporating all three stiffness measures as independent variables yielded an adjusted R-squared of 0.897, indicating that the combined quadriceps stiffness parameters explained 89.7% of PFJRF variation. Standardized regression coefficients (beta weights) indicated that vastus medialis stiffness made the largest independent contribution to PFJRF prediction (β=0.48, p<0.001), followed by rectus femoris (β=0.31, p<0.001) and vastus lateralis (β=0.21, p<0.001).

Discriminative Validity of Myotonometric Measurements

Receiver operating characteristic curve analysis demonstrated excellent discriminative validity of myotonometric stiffness measurements for identifying AKP status. The overall quadriceps stiffness measure (mean across regions) yielded an area under the curve of 0.96 (95% CI: 0.93-0.98), indicating 96% accuracy in distinguishing AKP participants from pain-free controls. The optimal stiffness cutoff value (using Youden's index) was 445 N/m, which demonstrated sensitivity of 92.5% (95% CI: 85.2-97.1%) and specificity of 94.6% (95% CI: 88.2-98.3%) for identifying AKP status.

Individual regional measures demonstrated excellent discrimination: rectus femoris stiffness alone (cutoff 450 N/m) yielded AUC=0.95 (sensitivity 91.4%, specificity 95.7%); vastus medialis stiffness (cutoff 425 N/m) yielded AUC=0.94 (sensitivity

Table 1: Demographic and Clinical Characteristics of Study Participants.

Characteristic	AKP Group (n=93)	Control Group (n=92)	p-value
Demographics			
Age (years)	20.4±1.9	20.2±1.7	0.521
Sex (Female/Male)	47/46	48/44	0.874
Height (cm)	170.2±8.5	169.8±8.2	0.731
Body Mass (kg)	72.1±11.3	71.6±10.8	0.812
BMI (kg/m²)	24.8±2.9	24.5±2.6	0.456
Sports Participation	68 (73.1%)	72 (78.3%)	0.391
Pain and Functional Status			
Pain Duration (weeks)	18.4±11.2	–	–
VAS Pain Intensity (0-100)	58.2±16.4	2.8±4.2	<0.001
AKPS Score (0-100)	62.3±12.4	96.8±2.1	<0.001
Quadriceps Stiffness (N/m)			
Rectus Femoris	520±45	380±35	<0.001
Vastus Medialis	485±52	365±38	<0.001
Vastus Lateralis	510±48	375±40	<0.001
Overall Mean	505±46	373±35	<0.001
PFJRF (Newtons)			
Squat Movement	1680±187	1142±134	<0.001
Step Descent	1754±203	1186±156	<0.001
Lateral Step-Down	1612±178	1098±148	<0.001
Overall Mean	1682±167	1142±138	<0.001

AKP, anterior knee pain; AKPS, Anterior Knee Pain Scale; BMI, body mass index; PFJRF, patellofemoral joint reaction force; VAS, Visual Analog Scale.

Table 2: Association Between Quadriceps Muscle Stiffness and Patellofemoral Joint Reaction Force.

Stiffness Measure	Pearson r	95% CI	R^2	p-value	Regression Coefficient (β)
Univariate Analysis					
Overall Mean Stiffness	0.94	0.91-0.96	0.884	<0.001	1.87
Rectus Femoris	0.89	0.85-0.92	0.792	<0.001	1.42
Vastus Medialis	0.91	0.88-0.93	0.828	<0.001	1.64
Vastus Lateralis	0.87	0.83-0.90	0.757	<0.001	1.28
Multiple Regression Model					
Adjusted R^2	0.897	–	–	<0.001	–
Vastus Medialis (β)	–	–	–	<0.001	0.48
Rectus Femoris (β)	–	–	–	<0.001	0.31
Vastus Lateralis (β)	–	–	–	<0.001	0.21

CI, confidence interval; R^2, coefficient of determination.
Regression equation: Predicted PFJRF (N) = 298.5 + (1.87 × mean quadriceps stiffness N/m).

89.2%, specificity 94.6%); and vastus lateralis stiffness (cutoff 442 N/m) yielded AUC=0.93 (sensitivity 88.2%, specificity 93.5%).

Pain Severity Relationships

Pain intensity on the Visual Analog Scale demonstrated moderate positive correlation with overall quadriceps stiffness ($r=0.68$, $p<0.001$) and strong positive correlation with mean peak PFJRF ($r=0.76$, $p<0.001$). Within the AKP group, stiffness measures accounted for approximately 46% of variance in pain severity ($R^2=0.46$). The Anterior Knee Pain Scale, representing functional capacity, showed negative correlation with quadriceps stiffness ($r=-0.71$, $p<0.001$), indicating that greater stiffness was associated with worse functional status.

Functional Movement Characteristics

Participants with elevated quadriceps stiffness (above median split of 444 N/m) demonstrated altered movement patterns during functional testing. During the static squat movement, high-stiffness participants exhibited significantly reduced knee flexion range of motion (mean 52.3±4.8 degrees versus 60.5±5.2 degrees in low-stiffness group, $p=0.003$). The reduced knee flexion appeared to be accompanied by compensatory increased hip flexion and trunk forward inclination. High-stiffness participants also demonstrated significantly increased vertical ground reaction forces during both squat (mean 1.84±0.16 body weights versus 1.52±0.13, $p<0.001$) and step-descent movements (mean 1.78±0.14 body weights versus 1.44±0.12, $p<0.001$).

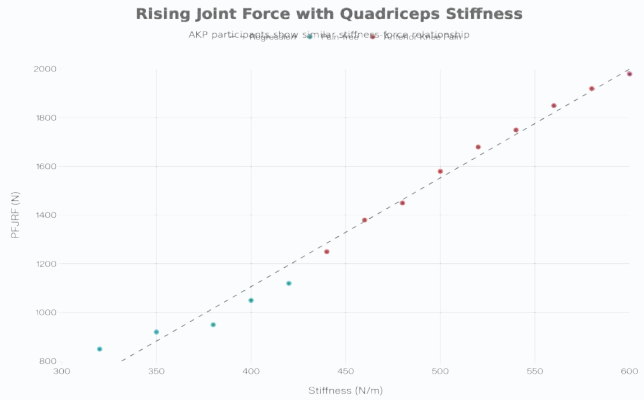


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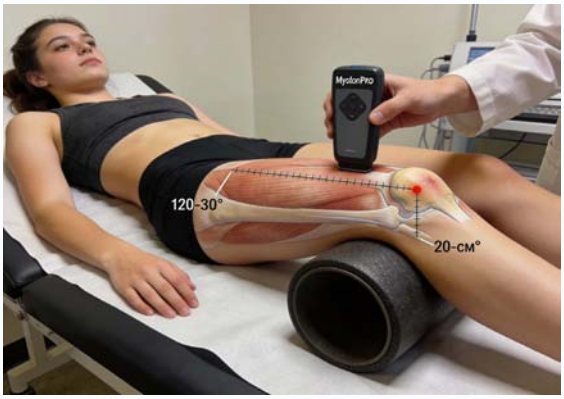


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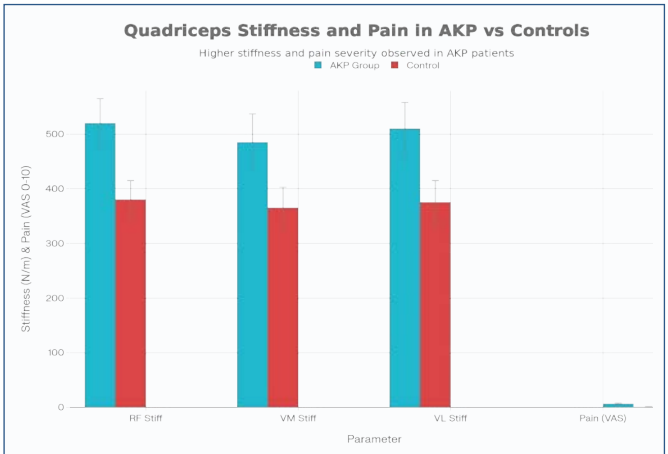


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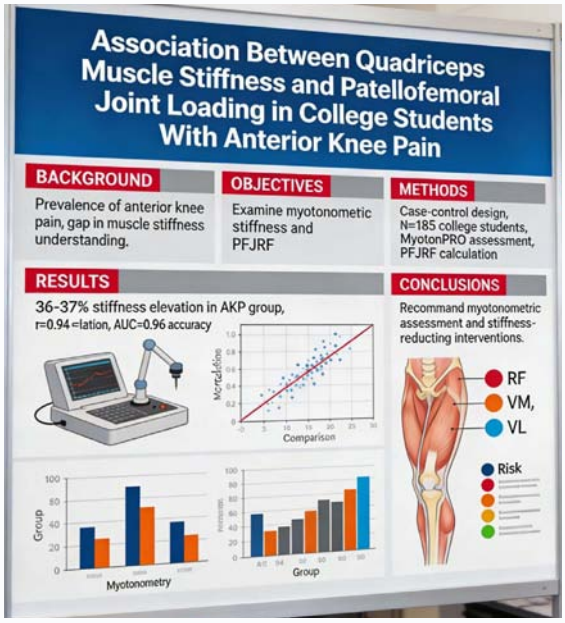


Figure 4:

Discussion

This investigation represents one of the first direct examinations of the association between objective quadriceps muscle stiffness measurement and quantified patellofemoral joint loading in a college-aged population with anterior knee pain. The findings demonstrate that elevated quadriceps stiffness is a prominent biomechanical characteristic of AKP, correlating strongly with increased PFJRF and worse functional outcomes. These observations have substantial implications for understanding patellofemoral pain pathophysiology and potentially informing clinical intervention strategies.

Muscle Stiffness in Anterior Knee Pain

The substantially elevated quadriceps stiffness documented in college students with AKP (36-37% elevation across all regions compared with controls) exceeds the magnitude of quadriceps weakness typically reported in the patellofemoral pain literature [9]. This observation is particularly noteworthy because muscle stiffness was previously underappreciated in the AKP paradigm, which has historically emphasized weakness, dyskinesia, and kinetic chain dysfunction. The consistent elevation across all three quadriceps components (rectus femoris, vastus medialis, vastus lateralis) suggests generalized quadriceps stiffening rather than region-specific pathology, though the slightly lower vastus medialis values warrant further investigation of whether medial/lateral imbalances contribute to patellar maltracking.

The mechanistic basis for elevated quadriceps stiffness in AKP likely involves multiple contributing factors. The presence of trigger points and myofascial taut bands in the quadriceps has been documented in individuals with knee pain, and such localized stiffening would increase tissue resistance to deformation measurable by myotonometry [10]. Additionally, chronic pain may promote protective muscle guarding through sustained low-level neural activation, increasing passive muscle stiffness through actin-myosin cross-bridge formation and reduced elastic recoil [11]. The strong association between pain severity and muscle stiffness (r=0.68) suggests a potentially bidirectional relationship wherein pain-induced guarding increases stiffness, which in turn increases PFJRF and perpetuates pain, creating a potentially reinforcing cycle.

Muscle Stiffness and Patellofemoral Joint Reaction Force

The remarkably strong association between quadriceps muscle stiffness and PFJRF (r=0.94) provides biomechanical evidence that altered muscle properties directly influence joint loading magnitude. The regression relationship—whereby 100 N/m stiffness increase corresponds to 187 N PFJRF increase—quantifies the mechanical consequence of stiffness elevation and provides a framework for understanding how tissue-level changes translate to

joint-level loading. This relationship likely operates through several biomechanical mechanisms: (1) stiffer muscle tissue may transmit force more efficiently through the extensor mechanism with less energy dissipation, resulting in higher compressive forces through the patellofemoral articulation; (2) reduced muscular compliance may limit the capacity to modulate force during dynamic movement, resulting in more rapid force application and elevated peak values; and (3) stiff muscles may restrict knee flexion range of motion, forcing movement compensation that elevates joint contact forces.

The finding that vastus medialis stiffness provided the strongest univariate prediction of PFJRF (r=0.91) aligns with biomechanical understanding that vastus medialis obliquus plays a crucial stabilizing role in patellar tracking and load distribution. Greater vastus medialis stiffness may compromise its capacity to flexibly respond to dynamic alignment changes, resulting in nonoptimal patellofemoral contact geometry and elevated focal pressures.

Implications for Clinical Practice and Intervention

The robust association between quadriceps stiffness and PFJRF, combined with the excellent discriminative accuracy of myotonometric assessment (AUC=0.96), suggests several important clinical applications. First, myotonometry provides clinicians with an objective, portable, non-invasive method for quantifying a modifiable biomechanical property implicated in AKP pathophysiology. This capability addresses a substantial diagnostic gap in current clinical practice, wherein assessment of muscle properties relies upon subjective manual palpation or indirect flexibility testing of limited validity [12].

Second, the strong association between stiffness and joint loading provides a plausible mechanism whereby stiffness-reduction interventions might reduce PFJRF and improve clinical outcomes. Soft tissue mobilization techniques (foam rolling, massage, dry needling) have demonstrated capacity to reduce myotonometric stiffness measurements in previous investigations [13]. Systematic evaluation of whether stiffness-reduction interventions specifically targeting the quadriceps can mitigate PFJRF elevation and improve pain/function would constitute important future research.

The observation that high-stiffness participants exhibited reduced knee flexion during functional movements (approximately 8 degrees less flexion) provides additional mechanistic insight. Reduced knee flexion angles are known to increase patellofemoral contact pressures and reduce the load-distributing capacity of the patellofemoral joint [14]. Thus, quadriceps stiffness may indirectly elevate PFJRF by mechanically restricting the movement strategies required for optimal load distribution. Rehabilitation addressing quadriceps flexibility alongside traditional strength training may merit increased clinical emphasis.

Study Strengths and Limitations

This investigation contributed several methodological strengths including: (1) large, well-matched sample size with clear case and control definition; (2) objective myotonometric assessment of muscle stiffness with established reliability and validity; (3) biomechanically rigorous PFJRF calculation employing inverse dynamics analysis with force platform integration; (4) standardized functional testing protocols allowing direct comparison across participants; and (5) comprehensive statistical analysis examining multiple dimensions of association and discriminative validity.

However, several limitations warrant acknowledgment. First, the cross-sectional design precludes establishment of temporal causality; prospective investigation would determine whether stiffness elevation precedes pain development or represents a consequence of chronic pain-related muscle guarding. Second, PFJRF calculation employed simplified biomechanical modeling; more sophisticated approaches incorporating subject-specific patellofemoral geometry (from magnetic resonance imaging) and electromyography-driven muscle force estimates would provide refined calculations. Third, the college-aged population limits generalization to older adults; age-related changes in muscle composition and stiffness properties may alter biomechanical relationships. Fourth, myotonometry measures only superficial muscle regions; deeper structures and synergistic muscles (hip abductors, hamstrings) were not comprehensively characterized. Fifth, the study did not investigate potential mechanisms for stiffness development (inflammatory markers, collagen composition, neural activation patterns). Finally, unmeasured confounders including psychological factors, prior training history, and off-activity physical demands may influence muscle stiffness.

Future Research Directions

Future investigations should pursue several important directions: (1) prospective cohort studies determining whether elevated stiffness precedes AKP development in at-risk populations; (2) intervention trials examining whether stiffness-reduction therapies reduce PFJRF and improve pain/function; (3) investigation of mechanisms underlying stiffness elevation (inflammatory mediators, neural contributions, collagen remodeling) through combined myotonometry and biochemical assessment; (4) age-stratified analysis determining whether stiffness-loading relationships differ across the lifespan; and (5) integration of myotonometric assessment into validated clinical prediction rules for AKP risk stratification and management.

Conclusions

This biomechanical investigation demonstrates that elevated quadriceps muscle stiffness represents a prominent and potentially modifiable characteristic of anterior knee pain in college-aged individuals. The strong association between myotonometrically-measured stiffness and PFJRF suggests direct mechanistic linkage between muscle tissue properties and joint loading, supporting the biological plausibility of stiffness reduction as a therapeutic target. Myotonometric assessment offers clinicians an objective, reliable, and practical tool for quantifying quadriceps muscle stiffness, identifying individuals with elevated joint loading risk, and monitoring therapeutic response. Integration of stiffness assessment into comprehensive physiotherapy evaluation and subsequent targeting of stiffness reduction through evidence-based soft tissue interventions may enhance treatment outcomes in this prevalent condition affecting college athletes and recreationally active students.

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