CRITICALLY APPRAISED TOPIC

FOCUSED CLINICAL QUESTION

In a 25-year-old athlete with a history of ACL injury, do deep squats or shallow squats impose less tensile and shear stress on the tibiofemoral joint and ACL?

AUTHOR

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CLINICAL SCENARIO

An outpatient sports specialist physical therapist is likely to encounter numerous young athletic patients who are recovering from a recent ACL injury. This patent might be in his mid-20s and an active participant in a contact sport such as basketball or football; he might be a student athlete whose scholarship is at risk, a young professional whose pay check is at risk, or a "weekend warrior" who views this sport as his favorite hobby.

This patient, in addition to safe rehabilitation of their ACL, will likely continue to require lower extremity strengthening exercises to help progress him or her towards return to sport. The squat exercise and its variants have been shown to be excellent tools for strengthening of the quadriceps, hamstrings, and hip musculature in a closed-chain, sports-specific manner. However, debate continues to surround appropriate "depth" of squat—that is, degree of knee flexion—with regards to injury risk and loading of various passive tissues. Understanding of the relationship between squat depth and ACL stress will allow a clinician to appropriately dose and customize therapeutic exercise appropriate to the patient's specific rehabilitative needs.

SUMMARY OF SEARCH

[Best evidence appraised and key findings]

Eight studies were initially included in this critically appraised topic, including **6 biomechanical cross-sectional experiments**, **one cadaveric randomized control trial**, and **one literature review**. A second search yielded an additional literature review that was deemed to be more recent and of higher quality than the initial review.

The overall **quality** of evidence was deemed to be relatively **low,** with most experiments considered **level 4** evidence. However, most studies were considered to have **moderate to high relevance** to the focused clinical question and scenario.

The literature review and one biomechanical cross-sectional experiment were chosen for the final critical appraisal.

Key findings are as follows:

- The ACL generally undergoes less stress in closed-chain exercises compared to open-chain exercises.
- The ACL generally undergoes less stress as knee flexion angle (squat depth) increases.
- The ACL generally undergoes maximal stress between 30 and 50 degrees of knee flexion in closed-chain squatting exercises.
- The peak tensile stress experienced by the ACL during deep squats is well below 25% of the estimated maximal tensile stress tolerable by a healthy ACL.

CLINICAL BOTTOM LINE

When viewing the ACL in isolation, closed-chain squatting to depths beyond 90 degrees of knee flexion appears to be the safest, lowest-stress exercise variation for safe lower extremity strengthening during ACL rehabilitation. Half-squats, where the knee is flexed to around 30 to 50 degrees, imposes the most stress on the ACL. Squat depth is a modifiable exercise variable that should be considered in the context of sports-specific rehabilitation goals, strengthening requirements, and other passive tissue injuries.

This critically appraised topic has been individually prepared as part of a course requirement and has been peer-reviewed by one other independent course instructor

The above information should fit onto the first page of your CAT

SEARCH STRATEGY

Terms used to guide the search strategy			
Patient/Client Group	**I**ntervention (or Assessment)	**C**omparison	**O**utcome(s)
Knee ACL Tear Injury Sprain Lower Extremity	Deep Squat Parallel Squat Full Squat Knee Flexion Range of Motion	Half Squat Partial Squat	Shear Tibiofemoral Kinematics Force Joint Load

Final search strategy (history):

Show your final search strategy (full history) from PubMed. Indicate which "line" you chose as the final search strategy.

1. (Knee OR ACL) AND (Tear OR Injury OR Sprain)
2. Squat
3. Deep OR Parallel OR Full
4. Half OR Partial
5. (#3 AND #2)
6. (#4 AND #2)
7. Depth OR Angle OR Flexion
8. (#7 AND #2)
9. (Tibiofemoral OR Knee OR ACL) AND (Shear OR Strain OR Stress)
10. Kinematic* OR Biomechanic*
11. #9 AND #11
12. **#1 AND (#5 OR #6 OR #8) AND #9**
13. **#1 AND (#5 OR #6 OR #8) AND #11**

In the table below, show how many results you got from your search from each database you searched.

Databases and Sites Searched	Number of results	Limits applied, revised number of results (if applicable)
Cochrane Library	**1,008 trials, 8 reviews**	**- Search terms included different variations of keywords including "squat" "shear" "acl"; Title Abstract search of "squat shear" resulted in 3 trials, one of which was selected**
PubMed	**28**	**- Search strategy described above yielded 28 results, 5 of which were selected**
Embase	**108**	**- "acl squat" revised to "acl squat shear" resulted in 5 results, 2 of which were selected** **(more details included below)**

INCLUSION and EXCLUSION CRITERIA

Inclusion Criteria
• RCT, systematic review, meta-analyses • Quasi-experimental designs • Cross-sectional studies • Anthropometric / kinematic / biomechanical lab data • Cadaveric studies and healthy subjects / patients
Exclusion Criteria
• Narrative reviews • Subjects >65 years of age • Not published in English • Case studies and case-controls n<15

RESULTS OF SEARCH

Summary of articles retrieved that met inclusion and exclusion criteria

For each article being considered for inclusion in the CAT, score for methodological quality on an appropriate scale, categorize the level of evidence, indicate whether the relevance of the study PICO to your PICO is high/mod/low, and note the study design (e.g., RCT, systematic review, case study).

Author (Year)	Risk of bias (quality score)*	Level of Evidence**	Relevance	Study design
Stuart MJ, Meglan DA, Lutz GE, Growney ES, An KN. (1996)[1]	**8/11 (PEDro)**	**Level 4**	**Low** (good comparison of various exercises, but not the exercises or variables outlined in my PICO question)	**Biomechanical / kinetic cross-sectional quasi-experiment**
Escamilla RF (2001)[2] ***Updated Search*** **Hartmann et al (2013)**[3]	**Low quality review, via AMSTAR** **Low quality review, via AMSTAR**	**Level 2** **Level 2**	**High** **High**	**Review** **Review**
Sahli S1, Rebai H, Elleuch MH, Tabka Z, Poumarat G. (2008)[4]	**8/11 (PEDro)**	**Level 4**	**Low** (measures relevant question, but only in the half squat; not compared to another intervention; main variable is load, not depth or knee flexion)	**Biomechanical / kinetic cadaveric cross-sectional quasi-experiment**
Beynnon BD1, Johnson RJ, Fleming BC, Stankewich CJ, Renström PA, Nichols CE. (1997)[5]	**8/11 (PEDro)**	**Level 4**	**Mod to Low** (again, measures the relevant question [ACL strain], but compares squat to open-chain leg extension, so wrong intervention/comparison)	**Biomechanical / kinetic cadaveric cross-sectional quasi-experiment**
Mulcahey MK, Monchik KO, Yongpravat C, et al. (2012)[6]	**9/11 (PEDro)**	**Level 2b**	**Low**	**Low-quality cadaveric randomized control trial;** (randomization and control variables were two ACL reconstruction types vs. intact knees; knee flexion measurement was not varied)
Li G1, Zayontz S, Most E, DeFrate LE, Suggs JF, Rubash HE. (2004)[7]	**8/11 (PEDro)**	**Level 4**	**Mod** (knee flexion angles are not varied, but ACL and PCL forces are measured throughout a full-range of knee flexion in open chain; we might be able to draw inferences from this)	**Biomechanical / kinetic cadaveric cross-sectional quasi-experiment**

Toutoungi DE1, Lu TW, Leardini A, Catani F, O'Connor JJ. (2010)[8]	**8/11 (PEDro)**	**Level 4**	**Mod-to-high** (similar to above, knee flexion angles are not varied, but ACL and PCL forces are measured throughout a full-range of knee flexion during squats)	**Biomechanical / kinetic cross-sectional quasi-experiment**
Li G, Zayontz S, DeFrate LE, Most E, Suggs JF, Rubash HE. (2004)[9]	**8/11 (PEDro)**	**Level 4**	**Mod** (extremely similar setup and design as other Li et al study)	**Biomechanical / kinetic cross-sectional quasi-experiment**

*Indicate tool name and score

**Use Portney & Watkins Table 16.1 (2009); if downgraded, indicate reason why

BEST EVIDENCE

The following 2 studies were identified as the 'best' evidence and selected for critical appraisal. Rationale for selecting these studies were:

- Hartmann H, Wirth K, Klusemann M. **Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load.** Sports Med. 2013;43(10):993-1008. doi:10.1007/s40279-013-0073-6
- Toutoungi DE, Lu TW, Leardini A, Catani F, O'Connor JJ. **Cruciate ligament forces in the human knee during rehabilitation exercises.** *Clin Biomech (Bristol, Avon)*. 2000;15(3):176-187. doi:10.1016/S0268-0033(99)00063-7
- These two articles were chosen for the following reasons: 1) the **Harmann et al** review, while not a systematic review in the fullest sense, is still the highest quality study and most up-to-date *summary and review* of the current literature on this topic, and specifically addresses the relevant PICO question. Originally, the Escamilla review from chosen; however, an updated search revealed a more up-to-date review. The **Toutoungi et al** article specifically examines knee cruciate ligament shearing forces, as opposed to others which examines various other knee kinematics, and does this in live subjects performing the relevant exercise (the squat) and its variants. Selecting these two studies gives a nice variety of research types (a review and a specific biomechanical experiment in live subjects) and should allow for enough variety to make solid conclusions for my PICO question.

SUMMARY OF BEST EVIDENCE

(1) Description and appraisal of "*Analysis of the Load on the Knee Joint and Vertebral Column with Changes in Squatting Depth and Weight Load*" by Hagen Hartmann, Klaus Wirth, and Markus Klusemann (2013)

Aim/Objective of the Study/Systematic Review:
The primary aim and objective of this literature review is to assess the musculoskeletal safety of the squat exercise with varying knee flexion ("depth"), comparing half/quarter squats to deep squats. Specifically, mechanical loading of the passive soft tissues of the patellofemoral and tibiofemoral joints, meniscal and cartilaginous tissues, and tibiofemoral ligamentous and tendinous shear forces were considered. For the purpose of this paper and specific application to the PICO question, only aspects of this review relating to tibiofemoral and cruciate ligament shear forces will be considered.
Study Design [e.g., systematic review, cohort, randomised controlled trial, qualitative study, grounded theory. Includes information about study characteristics such as blinding and allocation concealment. When were outcomes measured, if relevant] Note: For systematic review, use headings 'search strategy', 'selection criteria', 'methods' etc. For qualitative studies, identify data collection/analyses methods.
This study is, in essence, a literature review, lacking many of the key features required of a full-scale systematic review. The authors' **Search Strategy** involved only one database—PubMed—with over 20 independent search terms involving combination and permutations of terms such as "squat," "knee," "weightlifting, "ligament," "loading," and more. Studies **included** were those published between March 2011 and January 2013. Additional **inclusion criteria** required calculated knee-joint force data, tensile forces on

tendons and ligaments, external load information, and both deep and half squats performed. **Exclusion criteria** included studies that measured only bodyweight quarter squats (without external load or a comparative deep squat group.) The review yielded **164 articles**. No details regarding quality assessment, risk of bias assessment, or additional appraisal strategies were provided.

Setting

[e.g., locations such as hospital, community; rural; metropolitan; country]

As this was a literature review, specific setting information is not applicable to this particular appraisal. The authors were independent collaborators between Goethe University in Frankfurt, Germany, and Charles Sturt University in Bruce, Australia.

Participants

[N, diagnosis, eligibility criteria, how recruited, type of sample (e.g., purposive, random), key demographics such as mean age, gender, duration of illness/disease, and if groups in an RCT were comparable at baseline on key demographic variables; number of dropouts if relevant, number available for follow-up]

Note: This is not a list of the inclusion and exclusion criteria. This is a description of the actual sample that participated in the study. You can find this descriptive information in the text and tables in the article.

Comprehensive data were not provided for all included participants in this literature review. A large majority of the participants in the included studies are competitive or recreational weightlifters with no significant injury status or history. A large quantity of additional studies included cadaveric samples (mainly, cadaveric knees in those aged 50 – 90 years.) Sex and gender variations appear mostly even, with multiple studies included which directly compare males to females. The age of included participants varies, but generally includes large cohorts aged 12-20, 13-16, and other cohorts with a mean age of 59.3 and 59.7 years. Large population subsets specific to the measurement of ACL strain had a mean age of 26.1 and 24.9 years, making these populations particularly relevant to the PICO question. The included studies were ultimately categorized and discussed between the following categories: i) Mechanical Loading of the Patellofemoral and Tibiofemoral Joints; ii) Meniscal and Cartilage Adaptation Effects; iii) Meniscal and Cartilage Pressure Thresholds; iv) Tibiofemoral and Ligamentous Shear Forces; v) Tendinous Properties and Adaptations; vi) Spinal Joint Adaptation and Damage Effects.

Intervention Investigated

[Provide details of methods, who provided treatment, when and where, how many hours of treatment provided]

Control

- At least 8 studies included in this review contained control populations. These were generally cross-sectional biomechanical or anatomic studies comparing degeneration, stability, or cross-sectional area of various tissues between age-matched populations (e.g., weightlifters) and controls (e.g., untrained individuals.)
- Two of these studies are specifically applicable to the PICO question:
- One study compared knee ligament stability between weightlifters, powerlifters, and a control group with no weightlifting experience.
- One study compared cross-sectional area of the ACL and PCL of professional weightlifters to age-matched controls with no weight training experience.

Experimental

- Tensile strengths of the ACL and PCL were calculated via cadaveric data from **3** different studies, separated between age ranges (<26, 16 to 35, and 53 to 98 years.)
- **8** studies were included that calculated posterior shear forces during variations of the squat exercise through cross-sectional biomechanical methods.
- **4** of these studies included calculated values regarding percentage of maximal tensile strength imposed on the cruciate ligaments during the squat.
- **6** studies calculated anterior shear forces during the squat exercise at varying depths, using similar cross-sectional biomechanical study designs.
- **3** trials performed training interventions involving squats of varying depths for 8 to 21-week durations and examined knee ligament stability. An additional study compared the effects of squats on ligament stability as compared to running and basketball training interventions.

Outcome Measures

[Give details of each measure, maximum possible score and range for each measure, administered by whom, where]

No specific outcome measures or assessments were discussed in this review. Most experimental trials discussed above assessed ligamentous stability using mm of tibial displacement as assessed via the anterior drawer, compliance index, posterior drawer, and quadriceps active drawer clinical tests. Other biomechanical trials assessed tibiofemoral kinetics via EMG activity and 3D motion capture devices. Conclusions and reported results of included trials consisted of ACL and PCL forces (in Newtons, and as a factor of bodyweight when available.)

Main Findings

[Provide summary of mean scores/mean differences/treatment effect, 95% confidence intervals and p-values etc., where provided; you may calculate your own values if necessary/applicable. You may summarize results in a table but you must explain the results with some narrative.]

This literature review was notably limited in terms of statistics provided. No meta-analysis was performed, and no information is explicitly provided with regards to effect sizes, confidence intervals, or even statistical significance.

The authors provide calculated estimates of the maximal tensile forces of the ACL (1,730 ± 660 N and 2,160 ± 157 N for 16 to 35 years old) and PCL (4,000 N for subjects under 26 years old).

The authors found 500 N of anterior shear force during a 250 kg deep squat, which was maximal during the final 30 degrees of knee extension. They found 251 N of anterior shear force during a parallel squat, which was maximal during the final 22 degrees of knee extension. The half squat resulted in 719 N—the most of all squat variations—which peaked at the final 42 degrees of knee extension.

The anterior shear forces during parallel and deep squats account for between 11.62% and 28.9% of the maximal tensile strength of the ACLs of 16 to 35-year-old. The half squat accounts for 33.29% to 41.56% of the maximal tensile strength.

These summarized findings indicate that deeper squats apply less force to the ACL compared to half or above parallel squats, and that the shear stress applied to the ACL is maximized between 22 and 42 degrees of knee flexion.

Original Authors' Conclusions

[Paraphrase as required. If providing a direct quote, add page number]

"Based on these calculations, in deep squats, neither posterior nor anterior shear forces may reach magnitudes that could harm an intact PCL and ACL." (p. 9)

Deep squats appear to impose less shear and tensile stress on the anterior cruciate ligament when compared to parallel, half, and quarter squat variants.

Critical Appraisal

Validity

[Summarize the internal and external validity of the study. Highlight key strengths and weaknesses. Comment on the overall evidence quality provided by this study.]

The **AMSTAR Checklist** rated this review as **low quality**. Key <u>weaknesses</u> that underscore this poor rating include only one database searched (PubMed), no discussion of risk of bias assessment, no explanation of inclusion of RCT vs. NRSI, no discussion of duplicate study selection or data extraction, no list of excluded studies provided, no discussion of funding sources, no meta-analysis performed, and minimal discussion of heterogeneity. The majority of studies looked at healthy populations without injury history, or older cadaveric tissues.

Key <u>strengths</u> include a large number of articles included in the review (n = 164) and a thorough discussion and summary of multiple studies specific to the PICO question at hand. A large variety of study designs were included (biomechanical cross-sectional designs, cadaveric studies, EMG and motion capture data, animal models, calculations and extrapolations) which allow the authors to make nuanced conclusions. Many trials included patient populations at or near the age of the target population in the PICO question.

Overall, the quality of evidence for this study is relatively **poor**, taking into account the aforementioned AMSTAR rating and multitude of factors missing to make this a higher quality *systematic* review.

Interpretation of Results

[This is YOUR interpretation of the results taking into consideration the strengths and limitations as you discussed above. Please comment on clinical significance of effect size / study findings. Describe in your own words what the results mean.]

Despite the myriad weaknesses in study design, this review does an adequate job of summarizing and synthesizing a variety of studies and trials specific to the PICO question and beyond. Calculated data regarding tensile stress on the ACL during varying depths of squat, combined with additional calculated data identifying the maximal tolerable stress the ACL is able to tolerate before failure, seem to indicate that deep squats, at the very least, pose no more significant injury risk to the ACL when compared to half or partial squats. Additional data suggest that deeper squats impose *less* stress on the ACL (though more stress on the PCL) compared to half squats. The highest ACL stress occurs during the final ~30 degrees of knee extension, reinforcing the notion that partial squats would place a higher stress on the ligament. Lastly, deeper squats tend to use reduced load when compared to half or partial squats, which could possibly account for the reduced loads on the knee despite increased range of motion.

Applicability of Study Results

[Describe the relevance and applicability of the study to your clinical question and scenario. Consider the practicality and feasibility of the intervention in your discussion of the evidence applicability.]

The applicability of this study to my specific clinical question and scenario is mixed. As previously noted, the majority of studies included in this review involved intact ACLs in populations with notable injury history. Indeed, this review emphasizes *risk of injury* as opposed to *rehabilitation of injury*. With that said, this review provides hard data and actionable information regarding the **intervention** and **comparison** in my PICO question, explicitly answering the question as to whether deep squats or more or less stressful on the ACL and related tissues.

(2) Description and appraisal of "*Cruciate ligament forces in the human knee during rehabilitation exercises*" by Toutoungi et al (2000)

Aim/Objective of the Study/Systematic Review:

The aim of this study was to measure forces on the cruciate ligaments of the knee during a variety of rehabilitation exercises, specifically variations of the squat, and isometric and isokinetic knee extension activities. These forces were to be calculated mathematically using external force and limb kinematic data obtained in a biomechanics lab.

Study Design

[e.g., systematic review, cohort, randomised controlled trial, qualitative study, grounded theory. Includes information about study characteristics such as blinding and allocation concealment. When were outcomes measured, if relevant]

Note: For systematic review, use headings 'search strategy', 'selection criteria', 'methods' etc. For qualitative studies, identify data collection/analyses methods.

This study is a biomechanical cross-sectional design. No blinding was performed. There was no control group. The order of exercises performed, as well as the speed during isokinetic exercises, was randomized across subjects. The experimental design was broken into two sets, each using eight subjects; the first set analysed the right leg during isometric and isokinetic leg exercises, and the second set analysed the right leg during squatting exercises. Exercises utilized a dynamometer, as well as electromyography ("EMG") on the right leg. Isometric and isokinetic leg extension and flexion exercises were performed at varying speeds and knee flexion angles, the other of which were randomized between subjects. The squat exercise was performed without additional load with the subjects standi ng on a force plate, with data from two trials of a "heel-on-ground" and "heel-off" each recorded. Lastly, calculations of lower limb kinetics, intersegmental forces, and force distribution were made using advanced geometrical lower limb modelling combining the aforementioned EMG data.

Setting

[e.g., locations such as hospital, community; rural; metropolitan; country]

The experimental protocol was carried out in biomechanical motional analysis laboratories in varying locations. Author affiliations and locations include Cambridge and Oxford, UK, as well as the Movement Analysis Laboratory in Bologna, Italy, and the School of Physical Therapy in Taiwan.

Participants

[N, diagnosis, eligibility criteria, how recruited, type of sample (e.g., purposive, random), key demographics such as mean age, gender, duration of illness/disease, and if groups in an RCT were comparable at baseline on key demographic variables; number of dropouts if relevant, number available for follow-up]

Note: This is not a list of the inclusion and exclusion criteria. This is a description of the actual sample that participated in the study. You can find this descriptive information in the text and tables in the article.

There was a total of n = 16 subjects, with 8 participating in each experimental set. The isometric / isokinetic cohort consisted of 8 subjects with a mean age of 26.6 years (range: 22 to 35 years) and a mean weight of 158.4 pounds. The squat cohort consisted of 8 subjects with a mean age of 29 years (range: 23 to 35 years) and a mean weight of 171 pounds. The subjects are described as healthy and active with no known prior injury history or knee pathologies. Additional criteria regarding gender, recruiting methods, or other information is not provided.

Intervention Investigated

[Provide details of methods, who provided treatment, when and where, how many hours of treatment provided]

Control

As every subject participated in their associated experimental set, there is no control group to note. All data were taken from each subject's right leg, with no comparative data from the left leg provided.

Experimental

Two experimental protocols were performed:

Isometric and Isokinetic Exercises

Subjects performed single-leg extension and flexion exercises in a seated dynamometer at varying speeds (isokinetic) and varying knee flexion angles (isometric.) Subjects were instructed to perform the exercise as fast or as hard as possible. Isokinetic speeds, order of flexion and extension exercises, and knee flexion angles were randomized within the cohort. Knee flexion angles were 15, 30, 45, 60, and 75 degrees, and isokinetic speeds were 60, 120, and 180 degrees per second.

Squatting Exercises

EMG data were collected from the rectus femoris, biceps femoris, gastrocnemius, gluteus maximus, tibialis anterior, and tensor fasciae latae. While standing on a force plate, subjects performed multiple practice repetitions of a "heel-on-ground" and "heel-off" squat, and data from two trials of each squat were collected. The order of squat variations was randomized within the cohort. One-legged squats were performed by six subjects who were capable.

Outcome Measures

[Give details of each measure, maximum possible score and range for each measure, administered by whom, where]

No standardized outcome measures or assessments were used in this experiment. The data of interest were the calculated internal forces in the knee joint, mathematically determined from geometrical lower limb models and extrapolated from EMG and force plate data. These force data were compared to knee angles during each exercise.

Main Findings

[Provide summary of mean scores/mean differences/treatment effect, 95% confidence intervals and p-values etc., where provided; you may calculate your own values if necessary/applicable. Use a table to summarize results if possible.]

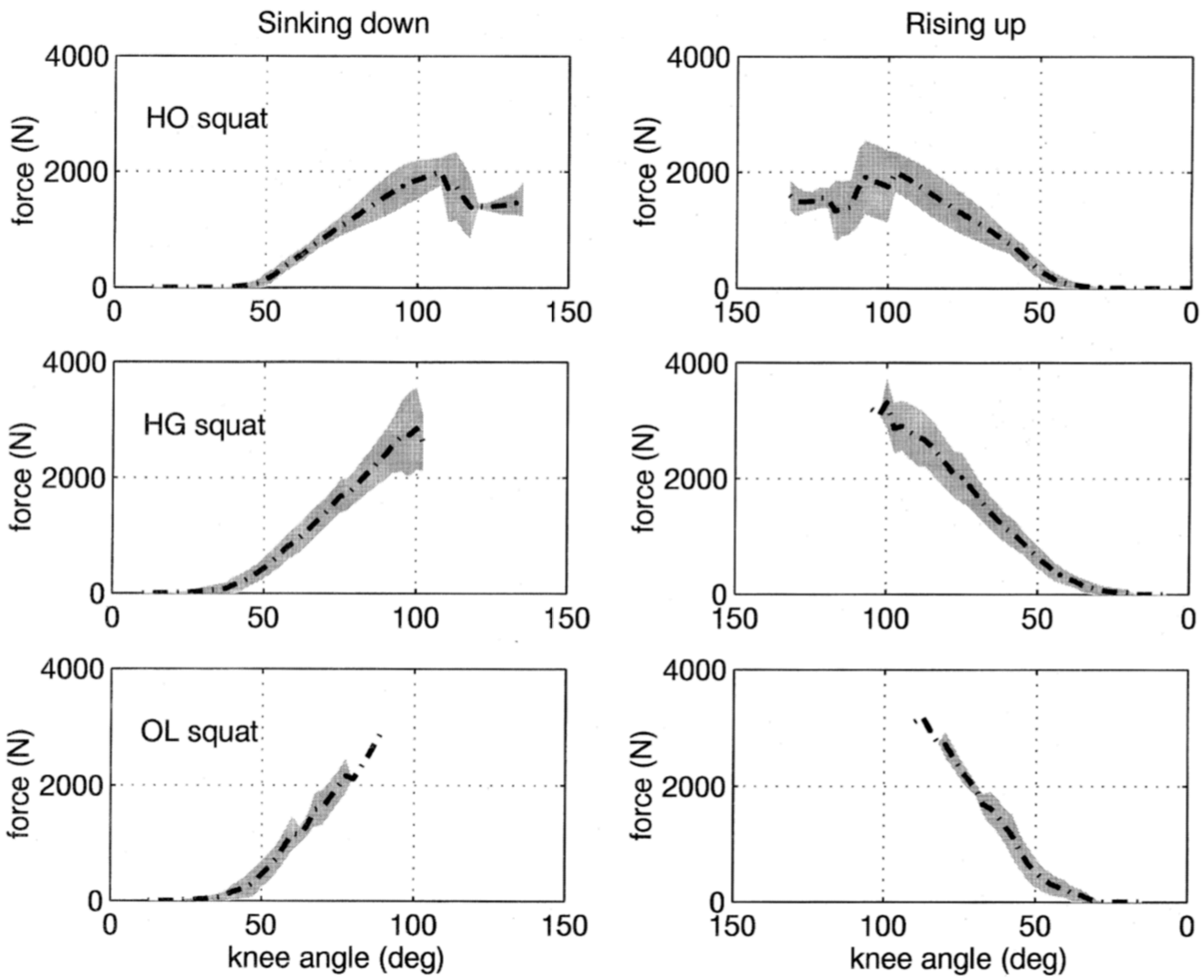
The mean peak ACL and PCL forces during each exercise are summarized in Table 1, shown below:

Table 1
Mean peak ACL and PCL forces occurring during the exercises[a]

Exercise type		Peak ACL force		Peak PCL force	
		(N)	(×BW)	(N)	(×BW)
Isokinetics					
Extension	60°/s	349 (110)	0.48 (0.15)	74 (72)	0.10 (0.10)
	120°/s	325 (72)	0.45 (0.10)	59 (61)	0.08 (0.08)
	180°/s	254 (91)	0.35 (0.13)	55 (42)	0.08 (0.06)
Flexion	60°/s	–	–	2701 (719)	3.8 (1.0)
	120°/s	–	–	2394 (775)	3.3 (1.1)
	180°/s	–	–	1952 (731)	2.7 (1.0)
Isometrics					
Extension		396 (106)	0.55 (0.15)	–	–
Flexion		–	–	3330 (1060)	4.6 (1.5)
Squats					
HO squat	Descent	95 (40)	0.12 (0.05)	2113 (217)	2.7 (0.3)
	Ascent	49 (57)	0.06 (0.07)	2222 (300)	2.8 (0.38)
HG squat	Descent	26 (31)	0.03 (0.04)	2432 (819)	3.1 (1.1)
	Ascent	28 (36)	0.03 (0.05)	2704 (805)	3.5 (1.0)
OL squat	Descent	117 (85)	0.15 (0.11)	1912 (665)	2.5 (0.9)
	Ascent	142 (67)	0.18 (0.09)	2246 (659)	2.9 (0.8)

[a] Values are expressed in Newtons (N) and as a fraction of body-weight (×BW). Standard errors in the mean are given in brackets.

Additionally, Figure 5 from the article displays posterior-directed cruciate forces during the ascending and descending phases of the three squat variations as compared to knee angles. Figure 5 is shown below:



The peak ACL forces were 396 Newtons, which occurred during isometric knee extension. All three squat variations had lower peak ACL forces compared to the open-chain exercises. Posterior cruciate ligament forces increase as squat depth increases, with the ACL forces acting inversely; ACL forces are highest at smaller knee flexion angles (i.e., shallower squats) and decrease throughout the range of motion, reaching their lowest values at the deepest angles of knee flexion. The maximal ACL forces in this study were found around 50 degrees of knee flexion, approximating a "half squat."

Original Authors' Conclusions

[Paraphrase as required. If providing a direct quote, add page number]

"During squats, relatively low ACL forces (less than 0.2xBW) occur when the knee angle is less than around 50°. At larger knee angles, the PCL is loaded, with the force increasing as the knee angle increases." (p. 11)

The authors drew numerous conclusions regarding the safety and effectiveness of isometric, isokinetic, and closed-chain lower extremity exercises, especially as they related to ACL and PCL rehabilitation. Specific conclusions regarding shallow vs. deep squats are limited, as that was not the direct aim of the study. Instead, conclusions regarding depth were drawn using table and chart data and a thorough reading of the Discussion section.

Critical Appraisal

Validity

[Summarize the internal and external validity of the study. Highlight key strengths and weaknesses. Comment on the overall evidence quality provided by this study.]

The **PEDro Scale** was utilized, with a score of **8/11** given. Due to the nature of the study design, many techniques, such as blinding and control groups were not realistic or feasible to implement. Randomization was utilized with good success as possible. Additionally, information regarding concealed allocation, baseline similarities within the cohort, thorough outcome measure obtainment, between-group statistical comparison, and variability measurements are all provided. The model used to calculate force data has been previously validated through similar study designs, and the outcome data are in agreeance with previously published data, lending some support of internal and external validity.

Weaknesses include the small cohort size (n = 8 for each experiment) and very limited demographic data provided regarding the subjects. The authors acknowledge limitations with the two-dimensional model utilized to calculate force data; for example, it is unable to calculate medio-lateral forces, was poorly personalized to individual geometric differences between subjects (e.g., unique patella-femoral joint geometries which would affect hamstring insertional moment arms.) The authors also acknowledge that the model tends to overestimate ligamentous forces, though for the sake of this PICO question, the data were able to provide a directional understanding of the relationship between ACL forces and knee flexion degree. Lastly, the model—and resultant force data—are mathematical, by definition; "in vitro" studies intending to measure these forces are invasive and quite destructive to the tissues, so mathematical calculations are the next best method.

Interpretation of Results

[This is YOUR interpretation of the results taking into consideration the strengths and limitations as you discussed above. Please comment on clinical significance of effect size / study findings. Describe in your own words what the results mean.]

It would appear that this biomechanical cross-sectional study, which utilized a variety of laboratory devices and mathematical models, confirms the findings discussed in the literature review previously appraised in this paper. A relatively linear and inverse effect of squat depth (knee flexion angle) is seen on ACL forces; that is, as squat depth increases, ACL forces appear to reduce concomitantly. Peak ACL forces are seen around 50 degrees of knee flexion, approximating a half squat. Additionally, peak ACL forces during squatting variants were quite low—no greater than 25% of the estimated maximal tensile load capabilities of the ACL. This study indicates that the deep squat is a safe exercise for ACL rehabilitation, especially when compared to alternative exercises or other shallower squat variations.

Applicability of Study Results

[Describe the relevance and applicability of the study to your clinical question and scenario. Consider the practicality and feasibility of the intervention in your discussion of the evidence applicability.]

The study design and its results do not *specifically* mirror my PICO question. In this study, the intervention and comparison were isometric and isokinetic open-chain exercises compared to closed-chain squat exercises; there was no explicit comparison between deep and shallow squats. Instead, conclusions had to be drawn through appraisal of the included tables and figures which provided ACL forces compared to knee flexion angles. The study would be more applicable if specific ACL forces were provided in table form at different knee flexion angles. This study does provide clinically-relevant information regarding rehabilitation exercise choices for ACL and PCL reconstruction or injury.

SYNTHESIS AND CLINICAL IMPLICATIONS

[Synthesize the results, quality/validity, and applicability of the two studies reviewed for the CAT. Future implications for research should be addressed briefly. Limit: 1 page.]

The two studies included in the critically appraised topic come to similar conclusions regarding the initial PICO question: deep squats (performed with knee flexion angles greater than 90 degrees) result in smaller peak forces on the ACL when compared to parallel, half, or partial squats.

The two studies attempt to answer this question through differing methods. Hartmann et al provide a literature review and summary that—albeit of relatively low quality from an evidence appraisal standpoint—adequately summarizes the most up-to-date literature of the subject. The review, which included over 164 studies, analysed a wide variety of tissue effects relating to the squat and its variants. This appraisal was limited to the aspects of the review focused specifically on ACL tensile load and tibiofemoral shearing forces. Toutoungi et al calculated cruciate ligament loads using a validated mathematical model and data from a biomechanics lab. This study compared the squat (with no parameters regarding depth) to isometric and isokinetic leg exercises; data regarding these open-chain exercises were not included in this appraisal, but data regarding ACL loads as compared to knee flexion angles in the squatting exercise proved useful.

Both studies found that peak ACL forces tend to occur in closed-chain squatting exercises around 30 and 50 degrees of knee flexion. This most approximates a shallow, partial, or half squat. Furthermore, ACL forces tend to decrease linearly as knee flexion angle increases, indicating that a deep squat is likely the *safest* exercise for rehabilitating an ACL injury. In both studies, peak ACL forces were found to be well below the maximal tensile stress of the ACL, even when using loads upwards of 250kg. Inverse relationships were seen in the PCL (deeper squats imposed profoundly greater stress on the PCL) and patellofemoral joint (deeper squats imposing more compressive force between the patella and femur.) These findings have important clinical implications: squat depth can, and should, be tailored specifically to the injured tissue.

These studies have some notable limitations. The majority of participants in these studies were healthy, active subjects with no significant injury history, all with intact ACLs, and many studies were relatively low-powered (Toutoungi et al, for example, only included 8 subjects.) Many trials included in the Hartmann et al review were performed on older cadaveric tissues, and others were retrospective reviews performed on cohorts sometimes as young as 12 years old. Furthermore, there are obvious limitations when using mathematical calculations and geometric models to determine internal forces; Toutoungi et al acknowledge this in their paper, but also note that invasive "in vivo" and "in vitro" studies are typically prohibitively unreliable and difficult to implement. Despite the obvious limitations and general low quality of evidence, it is fair to conclude that these studies comprise some of the best available evidence specifically examining this PICO question.

There are many future research implications worth briefly reviewing. Biomechanical cross-sectional studies, many of which will use mathematical modelling, will likely to continue to be status quo for this line of research, but increased variety of patient populations (e.g., those with an ACL injury or history of ACL injury) and larger cohort sizes would be prudent. More advanced information regarding maximal tensile load tolerance of intact ACLs, ligament grafts, and their rates of hypertrophy, strength, and healing could help inform more nuanced decisions regarding exercise selection. Lastly, future studies should attempt to be more deliberate with tracking and measuring of knee flexion angles and depths to provide a more thorough understanding of the effects of squat depth on ACL stress.

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