Biomechanics of Acromioclavicular Joint Reconstruction

Ph.D. Thesis booklet

Krisztián Kovács M.D.

Translational Medicine Program

Surgical Medicine Division

SEMMELWEIS UNIVERSITY

Supervisor: György Kocsis M.D., PhD.

Official reviewers: Imre Antal M.D., Ph.D.

Ling Qin M.D., Ph.D., DSc.

Head of the Complex Examination Committee:

Gábor Varga M.D., Ph.D.

Members of the Complex Examination Committee:

Miklós Szendrői M.D., Ph.D., DSc. Daniel Kendoff M.D., Ph.D.; Nelli Farkas M.D., Ph.D.; Bucsi László M.D., Ph.D.

Budapest

2025

1. *Introduction*

1.1.1 What is the topic?

This research explores implant behavior in musculoskeletal surgery from two perspectives: improving the accuracy of bone elasticity (Young's Modulus, E value) in finite element analysis (FEA), and evaluating complication rates and outcome variability with the Lockdown implant for AC joint dislocation.

1.1.2. What is the problem to solve?

Following the Lockdown surgery, we noticed an unusual complication. Rarely, the coracoid process may break off. Our initial idea was to try to build a finite element model to assess the stress and strain aspects of the coracoid, but we bumped into the problem of the large scatter of Young modulus values of bone in the literature. Therefore, we decided to take a systematic approach to clarify how much exactly the elastic modulus of the bone tissue is. The topic is approached from two aspects. Study I. aims to improve finite element analysis by highlighting the issue of validating bone's elasticity values. Finite element analysis is a numerical stress analysis technique that estimates the bone's Young's Modulus values (*E* values) from Computer Tomography (CT) data, which ignores the anisotropic feature of bone. Nevertheless, there is no standardized measurement method for ex vivo *E* value measurement, compromising the possibility of proper validation. The different *E* value measuring techniques can lead to two-fold magnitude differences in *E* values. With

the appropriate calculations, better implant designs could be created and planned before operation, which could help create a gold standard method for the surgical reconstructions in AC joint luxations, which is the centre of Study II. In that Study, we wanted to clarify the true incidence of coracoid fracture following this procedure, so we decided to build a study to assess the whole surgical procedure. During the assessment, the issue is the rate of complications and the heterogeneity of the shoulder score used for the efficacy of the Lockdown implant. Also, this heterogeneity and the low number of patients lead to fewer cases for comparison.

1.1.3. Why is it important?

Musculoskeletal implants are increasingly used due to sports injuries and aging populations. Hip and knee arthroplasties are expected to rise by 670% and 170% by 2030. In AC joint injuries, no gold-standard surgical technique exists among 150+ options. Inadequate treatment can impair quality of life.

1.1.4. What is the research impact?

This work aims to refine FEA modeling for implant design and planning, and to reduce clinical outcome variability in Lockdown procedures by recommending consistent scoring methods, improving comparability and future systematic reviews.

Supplementary Introduction

1.2.1. Finite Element Analysis and Young's Modulus

FEA models bone-implant interactions by assigning material properties to segmented CT-based meshes. However, ignoring bone's anisotropic nature can lead to ~50% error. Estimating E values from CT is limited, while mechanical tests (compression, US, nanoindentation) yield highly variable results—e.g., trabecular bone E values range from 0.61 to 60 GPa across studies. This study examines how demographic, specimen, and testing variables affect E values.

1.2.2. AC Joint Luxation and Surgical Management

AC joint injuries, 3.5–12% of shoulder injuries, are common in contact sports. Rockwood types I–II are treated conservatively; types III–VI typically require surgery. Over 150 techniques exist, including AC fixation (e.g., K-wires, hook plates), CC fixation, and graft-based reconstructions. Hook plates often require removal and have high complication rates (~26%). The Weaver–Dunn procedure is 70% weaker than native ligaments, with high recurrence and revision rates.

The Lockdown implant (formerly Surgilig) uses a double-braided polyester graft anchored between the coracoid and clavicle. It offers functional improvements with a low failure rate, but supporting evidence is limited by small sample sizes and study quality.

2. OBJECTIVES

2.1. Study I. - Anisotropy, anatomical region, and additional variables influence Young's modulus of bone: A systematic review and meta-analysis

Our goal was to examine the factors that influence E values in human bones. We hypothesized that a bone's Young's Modulus value is correlated with demographic information, specimen characteristics, and measurement details.

2.2. Study II. - Acromioclavicular reconstruction using the Lockdown technique: a case series and systematic review

Our study aimed to assess the efficacy, safety, and patient satisfaction of the Lockdown technique in treating Rockwood type III and above AC injuries at three Hungarian centers while comparing our findings with existing literature. We hypothesized that the Lockdown technique would be more effective in acute and non-revisional AC injuries than in chronic or revisional cases.

3. METHODS

This study followed the **PRISMA 2020** guidelines and the **Cochrane Handbook**. Protocols were registered in PROSPERO (Study I: CRD42021286292; Study II: CRD42024578461).

3.1. Study I

Anisotropy, anatomical region, and additional variables influence Young's modulus of bone: A systematic review and meta-analysis

Design & Sources:

A systematic search was conducted on Nov 21, 2021, in PubMed, Cochrane, and Embase using terms related to bone type and elasticity. No filters were applied.

Selection & Extraction:

Duplicates were removed via Endnote v21.0. Two reviewers screened titles/abstracts (Cohen's kappa = 0.99) and full texts (kappa = 0.84). Data were extracted by four authors in pairs and included author, country, publication year, measurement method, anatomical location, specimen size, condition, orientation, and E values (GPa).

Inclusion Criteria:

Human bone studies with in vitro E value measurements; case reports, series, and cohort studies with individual-level data. Excluded were imaging-based studies, animal or pediatric data, and patients with bone-affecting therapies or diseases.

Bias Assessment & Analysis:

Risk of bias was evaluated using the CARE tool (modified). Descriptive statistics and subgroup analyses were performed in Excel and R. Welch's t-tests assessed significance ($p<0.05$), and >10% differences were considered clinically relevant. Anisotropy was evaluated using Bland-Altman plots. Variable importance was calculated using a random forest model (R "party" package). Meta-analysis was not feasible due to data heterogeneity.

3.2 Study II:

Acromioclavicular reconstruction using the Lockdown technique: a case series and systematic review

3.2.1. Study II - Case-series

Design & Setting:

A multicentric retrospective study with prospective follow-up was conducted at three Hungarian centers between Jan 2018–Jan 2023. Ethical approval was obtained (ID: BMEÜ/2832-3/2022/EKU).

Participants:

Included were 39 patients (age >16) with isolated AC joint injuries. Exclusions: patients unable to consent or lacking follow-up data.

Data Collection:

Independent physicians collected data from records and follow-ups. Extracted variables included demographics, surgical details, Rockwood

classification, complications, and reoperations. Acute injuries were defined as ≤3 weeks from trauma.

Surgical Technique:

A standardized Lockdown procedure was used, involving coracoid loop fixation and clavicle stabilization with a cortical screw. All surgeons followed the same protocol.

Outcomes & Statistics:

Functional scores (OSS, CONSTANT, IMITANI, UCLA, DASH, ASES, SST, NRS) were assessed pre- and postoperatively. Data were analyzed in R and Excel using two-sample t-tests ($p<0.05$); boxplots illustrated subgroup comparisons.

3.2.2. Study II - Systematic Review

Search Strategy:

On Aug 10, 2024, a search was conducted across five databases using "acromioclavicular AND (lockdown OR surgilig OR synthetic)." No filters were used. One additional article was included manually.

Study Selection & Criteria:

Two reviewers screened studies (title/abstract kappa = 0.99; full-text = 0.91). Eligible studies involved Lockdown implants for Rockwood III+ injuries. Excluded were non-human, biomechanical, technique descriptions, reviews, or studies without clinical outcomes.

Data Items:

Data included author, country, sample size, gender ratio, age, follow-up, surgical details, time to surgery, scores (pre/post), complications, and

physiotherapy duration. Implant-related complications included cases where implant removal was necessary.

Data Synthesis & Bias:

Due to heterogeneity and limited reporting, a meta-analysis was not conducted. Results were summarized narratively and in tables. Risk of bias was assessed using the **JBI tool** and **ROBINS-I**.

4. RESULTS

4.1. Study I.

Search and Selection:

A total of 22,114 records were identified, of which 48 articles met the inclusion criteria and provided extractable E values.

Study and Cohort Characteristics:

These studies, published between 1966–2020 across 13 countries (most frequently the USA, France, and Belgium), included 756 bone entries from 397 human specimens. The most common bones tested were femur, tibia, and fibula, primarily using compressional, nanoindentation, and tensional techniques. Most specimens were cortical and wet, with subject ages ranging from 15 to 96 years. Over half were male, and sample thickness varied from 0.035 mm to 20 mm.

Subgroup Comparisons:

Cortical and cancellous bone showed distinct E value distributions. Focusing on femur, tibia, and fibula, age was associated with higher E values in cortical bones, particularly the femur (femur: 19.35±3.72 GPa for those above 60 years vs 14.57±9.21 GPa for those below 40 years; $p<0.001$). Male specimens had significantly higher E values in femoral cortical bone, except in bending tests. Dry specimens consistently exhibited higher stiffness than wet ones (dry: 22.42±2.36 GPa; wet: 16.87±6.33 GPa; $p<0.001$). Smaller samples <1 mm: 20.24±3.33 GPa; >1 mm: 17.22±6.25 GPa; $p<0.001$) generally showed higher E values in

cortical bone, though nanoindentation presented an inverse, nonsignificant trend.

A comparison was only possible for cortical specimens of the fibular and femoral diaphysis. In femoral specimens, the nanoindentation measurements had the highest E values (21.71±2.48 GPa), followed by compressional (17.93±4.13 GPa) and tensional measurements (15.38±4.24 GPa). The smallest E values were measured by bending (12.76±8.85 GPa). US entries could not be included in the comparison due to their low number. In the fibula, bending showed smaller E values (9.10±1.55 GPa) than US (17.14±1.89 GPa), but no other measuring method had a sufficient entry for comparisons.

Axial loading produced significantly greater E values than AP or ML directions across all bone types (Figure 4–5). Bland-Altman plots further confirmed anisotropic behavior in femoral cortical and cancellous bone.

In cancellous bone, femoral epiphysis E values were higher than metaphysis ($p=0.010$), and in the knee joint, tibial epiphysis was stiffer than the femoral ($p=0.026$).

Ranking:

Random forest analysis identified macrostructure, measurement method, and specific bone region as the most influential factors affecting E values. Direct regression was not feasible due to data limitations.

4.2. Study II. - Case-Series Study

Basic Characteristics:

Among 46 patients who underwent the Lockdown procedure, 39 (3 females, 36 males; mean age: 38.90 ± 12.68 years) had complete follow-up. Seven were lost to follow-up. The procedure was non-primary in 7 cases. Time from injury to surgery averaged 26.69 ± 84.36 weeks. Injury types were Rockwood III (54%), IV (15%), and V (31%). Mean follow-up was 24.51 ± 10.12 months. The dominant arm was injured in 17 cases. Return to work averaged 7.73 ± 9.95 weeks; physiotherapy lasted 5.38 ± 6.09 weeks.

Case-Series Outcomes:

Significant improvements were noted across all functional scores and pain levels. NRS scores improved significantly in acute (−2.26; p=0.013) and primary cases (−2.37; p=0.027). Visible deformity declined from 63% to 33% in acute and 75% to 8% in chronic cases. Postoperative scores were: OSS 44.92 ± 7.63, Constant 90.20 ± 15.08, Imitani 91.66 ± 16.36. OSS improved from 12.93 ± 7.14 to 44.56 ± 9.09 in acute, and from 29.17 ± 12.60 to 45.83 ± 2.29 in chronic cases (p=0.0017). All functional scores showed significant improvement, especially in acute and non-operated cases.

Case-Series Complications:

Twelve complications (30.8%) were recorded in 11 patients: 7 in acute, 5 in chronic groups. Infections (n=7) led to 4 revisions; 2 (5.1%) required implant removal due to deep infection (S. aureus, C. acnes). Re-

injury occurred in 4 patients (6–34 months post-op), 3 of whom had prior superficial infections. No implant migration was observed.

4.3. Study II - Systematic Review –

Basic Characteristics:

From 273 articles, 14 met inclusion criteria, with 9 suitable for data extraction involving 205 patients (mean age: 39.17 ± 2.96 years). Time to surgery averaged 27.18 ± 24.51 months. Return to work was 5–6 weeks; physiotherapy lasted 6–8 weeks. Patient satisfaction exceeded 90% in four studies.

Systematic Review – Outcomes:

Postoperative OSS (mean: 38.46 ± 13.36), Constant (85.46 ± 4.20), and Imitani (85.85 ± 6.57) were reported in 4–5 studies. Preoperative data were limited. Due to heterogeneity, meta-analysis was not feasible.

Systematic Review – Complications:

Overall complication rate was 34.6% (71/205). Implant-related issues (30.7%) included proud metalwork, loosening, stiffness, subluxation, and impingement. Superficial infections/discharge occurred in 8 cases. Fifteen reoperations (7.3%) were performed; implant removal occurred in 11 (5.4%) cases, with a total implant failure rate of 5.4%.

Risk of Bias:

Assessment revealed generally low levels of evidence due to study design limitations

5. CONCLUSIONS

1) We assessed the influence of various factors on the Young's modulus of bone. Notable differences were observed in macrostructure and anisotropy, particularly between the femoral epiphysis and metaphysis, as well as within the epiphysis of the distal femur and proximal tibia.
2) According to our results, the *E* value of the tibia in the knee joint was twice as much as that of the femur
3) The anisotropic properties of the bone had to be accounted for, which are missing in the "in silico" calculations.
4) Although a high complication rate was noted both in our cohort and in the literature, our findings indicate that the Lockdown technique is effective for treating primary and acute AC joint injuries, particularly in terms of functional outcomes. The consistently elevated complication rates across different surgical approaches suggest that the anatomical region itself may be inherently susceptible to complications.
5) In both studies, the literature misses important data, which prevents proper meta-analytic calculations.

6. BIBLIOGRAPHY

I. List of original publications within the topic of the PhD thesis:

1. **Kovács K**, Váncsa S, Agócs G, Harnos A, Hegyi P, Weninger V, Baross K, Kovács B, Soós G, Kocsis G, Anisotropy, Anatomical Region, and Additional Variables Influence Young's Modulus of Bone: A Systematic Review and Meta-Analysis, **JBMR PLUS** 7: (12) Paper: e10835, 13 p. (2023)

Scopus - Endocrinology, Diabetes and Metabolism SJR indikátor: Q1, Scopus - Orthopedics and Sports Medicine SJR indikátor: Q1, **IF: 3,4**

2. **Kovács Krisztián**, Váncsa Szilárd, Abonyi-Tóth Zsolt, Hegyi Péter, Soós Gergely, Rábai Kálmán, Bogosi Tibor, Kocsis György, Acromioclavicular Reconstruction Using the Lockdown Technique: A Case Series and Systematic Review, **JOURNAL OF CLINICAL MEDICINE** 14: (12) Paper: 4046, 16 p. (2025)

Scopus - Medicine (miscellaneous) SJR indikátor: Q1 **IF: 2,9**

II. List of original publications not relating to the topic of the PhD thesis:

3. Moghaddam MA, Perlaky T, **Kovács K**, Kiss J, Szalay K, Antal I, Sápi Z, Szendrői M A lágyrészszarkóma epidemiológiája egy hazai egyetemi centrumban [Epidemiology of soft tissue sarcomas in a university center in Hungary] **MAGYAR ONKOLÓGIA** 61: 4 pp. 368-373. (2017)

Scopus - Medicine (miscellaneous) SJR indikátor: Q4 ,Scopus - Oncology SJR indikátor: Q4

4. **Kovács Krisztián**, Bartha Lajos, Antal Imre, Felső ugróízülettel kommunikáló csontcysta sebészi kezelése súlyos A-haemophiliás betegen [Surgical treatment of a juxtaarticular bonecyst communicating with the ankle joint in a severe haemophilia A case] **ORVOSI HETILAP** 160: (17) pp. 679-682. (2019)

Scopus - Medicine (miscellaneous) SJR indikátor: Q3 **IF: 0,497**

5. Stubnya Bence Gusztáv, Kocsis Koppány, Váncsa Szilárd, **Kovács Krisztián**, Agócs Gergely, Stubnya Márton Péter, Suskó Eszter, Hegyi Péter, Bejek Zoltán Subvastus approach supporting fast-track total knee arthroplasty over the medial parapatellar approach: A systematic review and network metaanalysis **JOURNAL OF ARTHROPLASTY** 38: (12) pp. 2750-2758. (2023)

Scopus - Orthopedics and Sports Medicine SJR indikátor: D1, **IF: 3,4**

6. Skaliczki G, **Kovács K**, Antal I, Sallai I, Kovács B, Nyőgér Z, Géresi Á, Kiss B, Várnagy A, Arthroscopic capsular release is more effective in pain relief than conservative treatment in patients with frozen shoulder **BMC MUSCULOSKELETAL DISORDERS** 25: (1) Paper: 145, 7 p. (2024)

Scopus - Orthopedics and Sports Medicine SJR indikátor: Q2 Scopus - Rheumatology SJR indikátor: Q2 **IF: 2,4**