Prosthesis and Prejudice: Potential Bias, Procurement, and Prescribing Patterns in Canadian Knee Arthroplasty

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Background

Total knee arthroplasty (TKA) implant selection is influenced by patient, surgical, institutional, and implant-specific factors, yet national data describing these patterns in Canada remain limited. This thesis used data from the Canadian Joint Replacement Registry (CJRR) to characterize TKA implant use and examine variation in implant selection across Canada from 2019 to 2023.

Methods

An open-source implant reference library and validation pipeline were developed to improve the identification and classification of implant manufacturers and models. These tools were used to characterize national and provincial trends in fixation method, patellar resurfacing, implant stability, and manufacturer and model utilization. Finally, clustering methods were applied to identify latent implant prescribing configurations and assess whether patient characteristics explained cluster membership.

Results

The implant reference library substantially improved the usability and granularity of CJRR data and demonstrated potential for retrospective data validation. Cementless fixation increased substantially over the study period and was more common among male and younger patients. Patellar resurfacing and posterior-stabilized design utilization declined as medial-pivot designs increased, while cruciate-retaining designs remained relatively stable. Substantial provincial variation was observed across fixation, resurfacing, stability, and manufacturer- and model-level implant selection. Manufacturer trends indicated that some observed practice changes were likely influenced by market composition. Of note, the Stryker Triathlon system accounted for much of the shift toward cementless fixation. Clustering identified six distinct TKA prescribing configurations, primarily differentiated by fixation, stability, and implant model. Similar configurations emerged when model identity was excluded as a clustering input, demonstrating convergence on broad functional design categories across manufacturers. Patient characteristics did not substantially explain cluster membership.

Conclusion

TKA implant selection in Canada converged on broad functional design configurations alongside some model-specific trends (e.g., Stryker Triathlon cementless), with substantial variation across patient groups and provinces. The findings of this thesis suggest that market composition, procurement practices, and unmeasured institutional and surgical factors may contribute to the observed prescribing patterns. Strengthening registry data usability through standardized implant identification and incorporating additional surgical and institutional variables could enable more granular analyses of implant selection. Future research should link these prescribing patterns to clinical outcomes to determine whether observed variation influences patient care and identify opportunities to improve the quality and value of TKA in Canada.

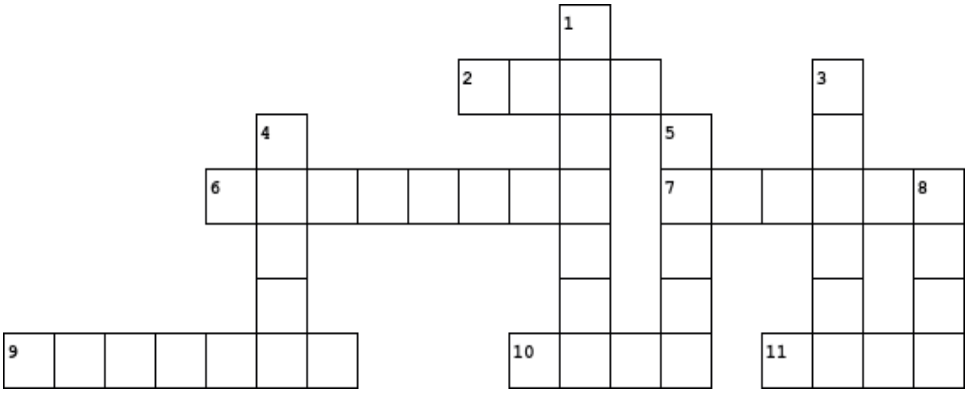
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Across

2. My Queen's collaborators, for all the gait data and letting me hang out in the lab.

6. My boyfriend, for encouraging me to make the most of every opportunity and supporting me through it all (and for always making extra bacon for me).

7. My Mom, for always feeding me and picking up my calls when Serena was busy.

9. My favourite CJRR analyst who painstakingly vetted every plot, table, and statistic in this thesis.

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1. My brother, for reminding me that hobbies are just as important as work.

3. My sister, for picking up my calls even when I had nothing to talk about.

4. My dad, for getting my jokes, and always having confidence in me.

5. My supervisor, for her support, mentorship, and belief in me (and the endless plant cuttings).

8. My dog, for never complaining about my complaining, and forcing me to go outside.

Artificial Intelligence Disclosure Statement

All tools listed in this statement were used between September 2025 and September 2026. Tools used included Claude by Anthropic; Grammarly's AI writing assistant; and Consensus AI.

Claude was used to assist with code development and debugging, and proofreading of manuscripts to identify areas of repetition, lack of clarity, and poor document flow; Grammarly's AI writing assistant was used to review and edit grammar, conciseness, and tone; Consensus AI was used to search for academic articles.

The author reviewed and edited the AI-generated content as needed and takes full responsibility for the content of this thesis.

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List of Abbreviations

AOANJRR Australian Orthopaedic Association National Joint Replacement Registry

AP Anteroposterior

AUROC Area Under the Receiver Operating Characteristic curve

BMD Bone Mineral Density

CI Confidence Interval

CIHI Canadian Institute for Health Information

CJRR Canadian Joint Replacement Registry

CR Cruciate-Retaining

DAD Discharge Abstract Database

eIFU electronic Instructions for Use

GMDN Global Medical Device Nomenclature

GTIN Global Trade Item Number

GUDID Global Unique Device Identification Database

IPL International Prostheses Library

MDALL Medical Devices Active Licence Listing

ML Mediolateral

MP Medial-Pivot

NACRS National Ambulatory Care Reporting System

OA Osteoarthritis

OR Odds Ratio

PCL Posterior Cruciate Ligament

PMMA Polymethylmethacrylate

PS Posterior-Stabilized

TKA Total Knee Arthroplasty

WEC Weighted Effects Coding

Graphical Abstract

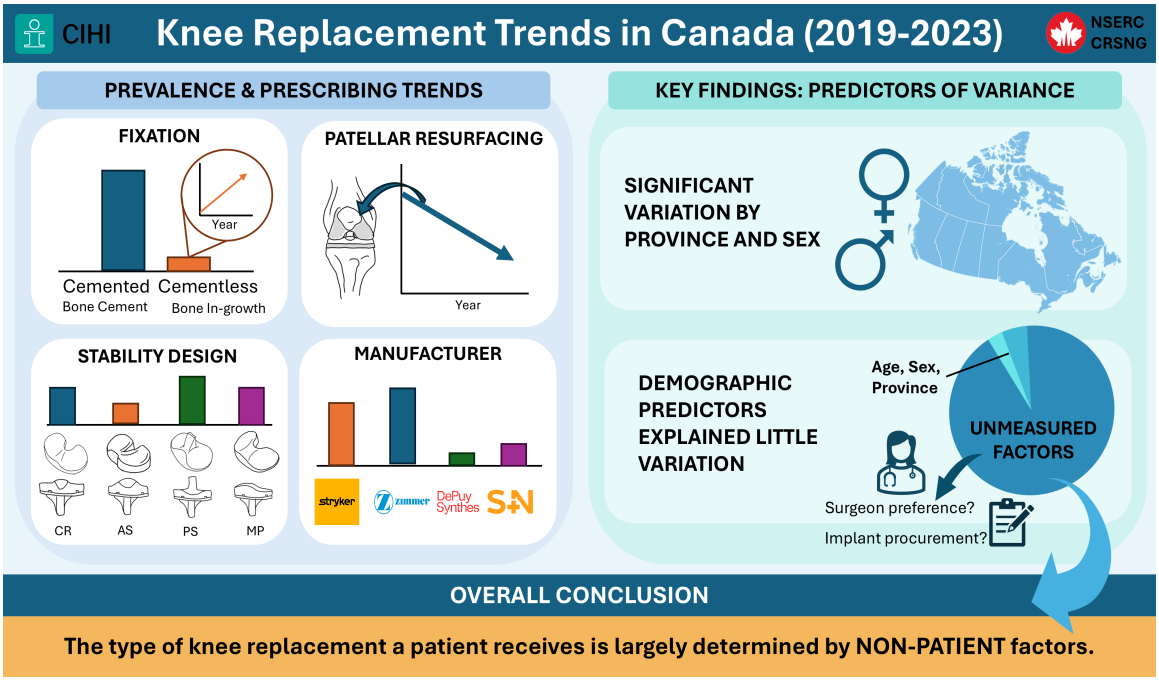


Figure 1: Graphical Abstract.

Chapter 1

Background

1.1 Overview

This thesis covers various topics in total knee arthroplasty (TKA) using data from the Canadian Joint Replacement Registry (CJRR), a national data system under the Canadian Institute for Health Information (CIHI), which collects and reports information on hip and knee arthroplasty procedures across Canada. Within the realm of TKA, this thesis discusses implant designs, manufacturers, and prescribing practices; therefore, this chapter provides the necessary background and context for the manuscripts presented in later chapters. This information includes the medical indications for TKA, the implant components of a TKA procedure, differences in each component's design features, and the manufacturers of those components. The thesis also presents information on how hospitals in Canada procure implants from these manufacturers, as TKA is not only a medical procedure but also a lucrative medical device market. Given the data source of this thesis, the role of arthroplasty registries in monitoring implant performance and patient outcomes, as well as the global context of national registries, is presented. This chapter also details information specific to CJRR processes. Moreover, it briefly reviews the statistical methods used in this thesis and their limitations. Finally, this chapter outlines the overarching research gaps, objectives, hypotheses, and approaches of this thesis.

1.2 Joint Replacement

1.2.1 Osteoarthritis and the Rationale for Arthroplasty

Osteoarthritis (OA) is a degenerative joint disease and the most common indication for total knee arthroplasty (TKA) [1]. The knee is a synovial joint comprising the patellofemoral and tibiofemoral compartments, stabilized primarily by the anterior and posterior cruciate ligaments, the patellar tendon, and the cartilaginous discs that facilitate articulation between the tibia and femur [2] (Fig. 1.1). Due to the distribution of weight through the knee, OA predominantly affects the tibiofemoral compartment. Progressive loss of the articulating cartilage and subsequent damage to the underlying subchondral bone causes joint space narrowing. This most commonly occurs in the medial tibiofemoral compartment, increasing varus deformity (but can also occur in the lateral compartment, increasing valgus alignment), in a cycle that progressively worsens knee function [2].

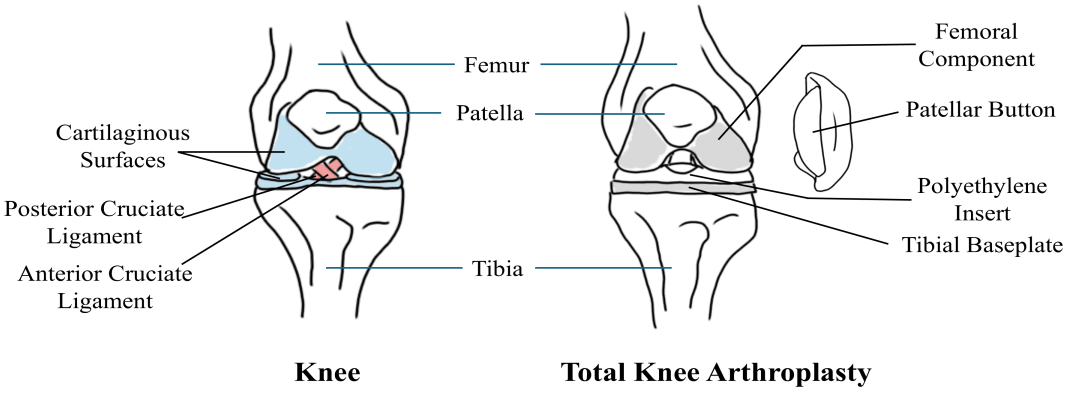


Figure 1.1: Knee anatomy and total knee arthroplasty components.

TKA addresses this degenerative cycle by replacing the damaged articular surfaces of

the femur, tibia, and (optionally) patella with prosthetic implant components (Fig. 1.1), with the aim of relieving pain and restoring function [2]. The first TKA procedure a patient receives is termed the primary (or index) procedure, whereas any future TKA procedures on the same knee would be considered revision surgeries. The Canadian Joint Replacement Registry (CJRR) has reported TKA as one of the most common procedures performed in Canada, with over 85,000 primary procedures recorded in 2024 and case volumes growing consistently [3,4]. Despite this, patient satisfaction remains suboptimal. An estimated 20% of patients remain dissatisfied following TKA, citing persistent pain, stiffness, or incomplete functional recovery [5], supporting the need for continued research in this field.

While TKA demand continues to rise with an aging population, compounded by surgical backlogs after the COVID-19 pandemic [5], demand also rises among younger patients, who face a longer remaining lifetime over which a primary implant must survive. This has renewed interest in fixation methods and implant designs intended to improve long-term performance [6,7]. Further research into implant performance, prescribing patterns, and health-system factors that shape TKA delivery is therefore relevant to both reducing revision burden and managing the growing demand for primary procedures.

1.2.2 Implant Components

A primary TKA typically involves three or four components: a femoral component, a tibial baseplate, a tibial (polyethylene) insert, and, if the surgeon elects to resurface the patella, a patellar component [2]. The femoral and tibial baseplate components are commonly manufactured from cobalt-chromium alloys or titanium, while the tibial insert and patellar button are polyethylene [2]. The femoral component is designed to reproduce the anatomy of the distal femur, including an asymmetrical anterior flange similar in shape to the native patellar groove, which helps prevent lateral dislocation of the patella. Similarly, the tibial component resembles the resected tibial plateau and is further stabilized by a keel or stem that seats into the tibial medullary canal [2]. Where disease is limited to a single compartment, a tissue-sparing unicompartmental design may be used instead, replacing only the damaged compartment [2].

Fixation of these components to bone has historically relied on polymethylmethacrylate (PMMA) bone cement, an approach considered the long-standing gold standard in TKA [2,8]. Cementless fixation, which instead relies on bone ingrowth into a porous metal implant surface, is discussed alongside cemented fixation in Section 1.2.3, since fixation method is one of the principal design variables surgeons select for each patient.

1.2.3 Implant Design Variables

Beyond the basic femoral-tibial-patellar configurations, TKA implants vary across several design features, including the level of constraint or stability provided by the polyethylene insert, whether the bearing is fixed or mobile, whether the patella is resurfaced, the fixation method, and the use of stems or augments. Each of these choices carries potential clinical and biomechanical consequences and is addressed below.

Stability, Constraint, and Bearing Design

The two dominant stability options in primary TKA are posterior cruciate ligament (PCL)-retaining, or cruciate-retaining (CR) designs and PCL-sacrificing, posterior-stabilized (PS), designs (Figs. 1.2 and 1.3). PS designs require both cruciate ligaments to be sacrificed and substitute a cam-post mechanism. During flexion, the cam located centrally on the femoral component engages the post on the tibial insert, preventing posterior dislocation of the femur [2,9]. CR designs instead leave the posterior cruciate ligament intact, which can allow for greater knee flexion, though this preservation requires more precise surgical technique to balance the retained ligament [2]. A systematic review and network meta-analysis comparing PS (ACL and PCL resected, post-cam mechanism), CR (ACL resected, PCL preserved), bi-cruciate substituting (ACL and PCL resected, asymmetric post-cam mechanism [10], specific to Smith & Nephew Journey model), and bi-cruciate retaining (ACL and PCL preserved) designs found a modest early advantage in range of motion for PS over CR designs, but no significant differences in range of motion, patient-reported outcomes, or complication and revision rates at longer-term follow-up [11]. Intraoperative sensor-based

comparisons of femoral rollback, the posterior translation of the femoral condyles during knee flexion, found that PS designs produced a greater percentage of rollback than CR designs, while CR designs preserved a more physiologic lateral-to-medial rollback ratio, underscoring the importance of soft-tissue balancing for restoring native knee function [12]

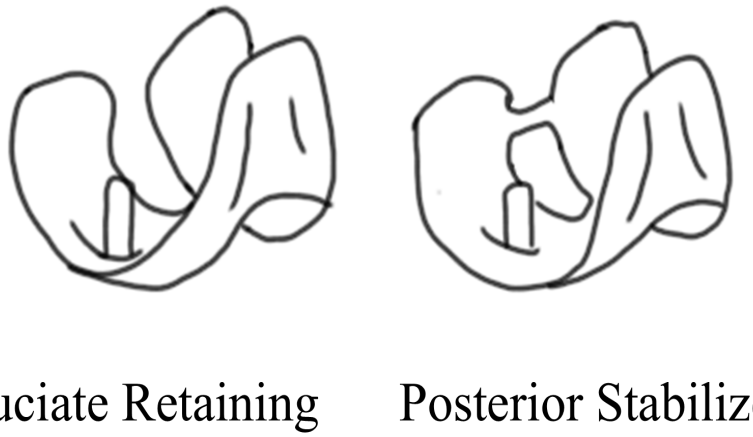


Figure 1.2: Cruciate retaining and posterior stabilized femoral components.

A related design is the medial-pivot insert, intended to more closely reproduce the asymmetric kinematics of the native knee, in which the medial compartment pivots while the lateral compartment translates more freely [9]. A prospective randomized comparison of medial-pivot and PS implants found that medial-pivot implants scored better on measures of deep flexion and prosthesis stability, including the Forgotten Joint Score [13]. Related simulation work on asymmetric tibial inserts, which aim to better accommodate the native asymmetry of the tibial plateau, has shown that asymmetric inserts can induce more physiologic posterior femoral positioning and greater axial rotation in the lateral compartment than symmetric inserts [14]. Moreover, an early multicentre clinical follow-up study of an asymmetric "kinematic retaining" implant reported favourable patient-reported outcomes and no revisions at two years [15].

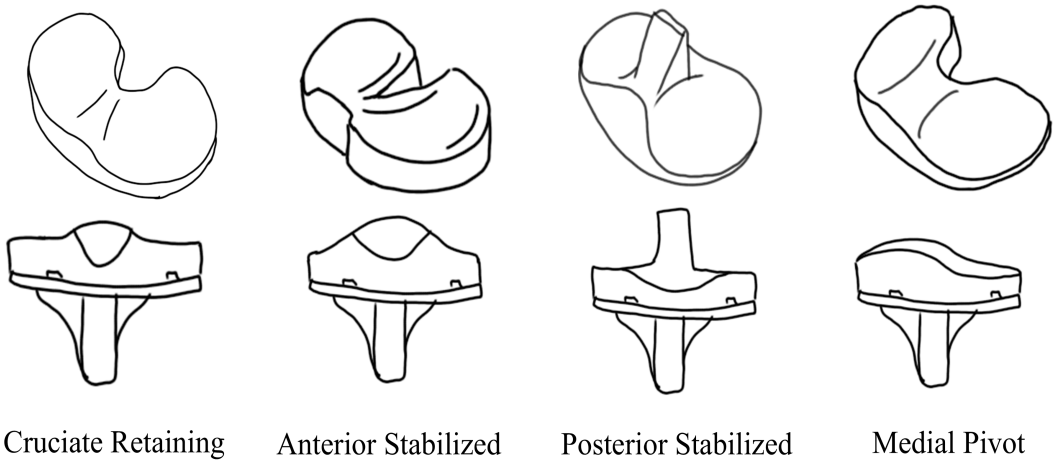


Figure 1.3: Polyethylene inserts (cruciate retaining, anterior stabilized, posterior stabilized, medial pivot) and tibial baseplates.

Bearing mobility is another design feature. Mobile-bearing (or rotating platform) allows the polyethylene insert to rotate freely on the tibial baseplate, enabling anterior-posterior and internal-external rotation at the baseplate-insert articulation [9] (Fig. 1.4). Due to this mobility, and its potential to self-adjust its position, it has been suggested that this design may reduce polyethylene wear and implant loosening and better accommodate subtle malalignments [15–19].

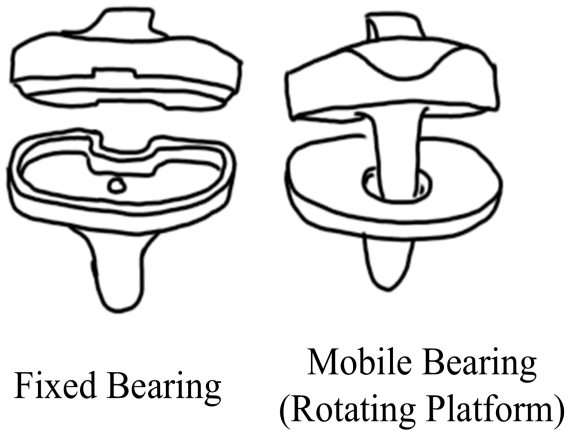


Figure 1.4: Fixed and mobile bearing tibial baseplates and polyethylene inserts.

Patellar Resurfacing

Anterior knee pain is one of the most common complications following TKA. Patellar resurfacing, in which the posterior surface of the patella is replaced with a polyethylene button, is often used as a strategy to address this, but its routine use remains debated in the literature [20–22]. Registry evidence illustrates how unresolved this debate is at a global level: Nordic registry data from 2000 to 2017 have shown that despite a documented decline in the use of posterior-stabilized designs in Denmark (a design category in which resurfacing is reported to reduce revision risk), rates of patellar resurfacing there remained essentially unchanged over the same period (averaging 79% of TKA procedures). In contrast, resurfacing was performed in less than 20% of TKAs in Finland, Norway, and Sweden during the same period [23,24]. This wide, seemingly practice-driven rather than evidence-driven variation in resurfacing rates across otherwise comparable health systems motivates closer study of Canadian prescribing practices in this thesis.

Fixation: Cemented and Cementless Designs

Cemented fixation relies on PMMA bone cement, which, contrary to its name, is not an adhesive but rather fills the gaps between the resected bone surfaces and the implant, providing immediate mechanical interlock and stability [25]. PMMA-based bone cement was first developed for orthopedic fixation in the 1960s and remains the most widely used material for anchoring joint replacement components to bone [26]. The cement is mixed and applied intraoperatively as a paste that cures through an exothermic polymerization reaction, hardening around irregularities in the bone surface to achieve mechanical, rather than chemical, fixation [26]. However, despite being the current gold-standard for fixation, cement use carries recognized risks, including intraoperative embolization of marrow, fat, or cement components during pressurization which has been associated with bone cement implantation syndrome [27], and once in place, the cement is susceptible to fatigue fracture and progressive aseptic loosening, which can make subsequent revision surgery considerably more technically demanding than revision of an uncemented implant [28]. Moreover, the time required for cement to cure intraoperatively also extends the duration that the surgical wound remains open, which has been raised as a potential contributor to infection risk, and represents a source of operative inefficiency that has motivated interest in operative methods that reduce surgery duration [26,29–33].

Cementless (uncemented) fixation instead depends on bone ingrowth, or osseointegration, into a porous or textured implant surface, avoiding the use of cement entirely [34,35]. Early cementless total knee systems were introduced in the 1980s, but first-generation designs were associated with comparatively high rates of early aseptic failure, and consequently, cementless fixation never gained much traction over cemented fixation methods [36–38]. One of the earliest porous-coated designs used a double layer of sintered chrome-cobalt beads to create an average pore size of approximately 425 μm and 35% porosity. Short-term (two-year) follow-up reported no clinical interface failures [39]; however, longer-term retrieval studies later identified shedding of these sintered beads as a mode of failure, which was associated with increased polyethylene wear and metal ion release [40–43]. However, one retrieval series found no correlation between the presence of loose beads and

clinical outcome [44]. Modern cementless implants have since benefited from advances in porous-coating materials, additive manufacturing, and surface design intended to promote osteointegration while preserving native bone stock [45–47], and more recent studies report survivorship comparable to that of cemented designs [34,35,48].

Successful bone ingrowth into a cementless implant surface depends on several factors. First, mechanical stability at the bone-implant interface during the early post-operative period. Excessive relative motion, or micromotion, between the implant and bone inhibits the formation of new bone at the interface and instead favours the formation of a fibrous, non-load-bearing membrane [38]. Therefore, successful ingrowth requires adequate initial press-fit and mechanical stability of the implant. Modern porous-metal surfaces, which combine high porosity with a lower effective elastic modulus than the older, denser implant designs, aim to improve frictional stability and reduce early micromotion [35]. Various manufacturers market proprietary porous-coating or "metal foam" technologies with these mechanical properties, used either as coatings or as stand-alone structural surfaces [47]. Surface roughness is also an important consideration for osseointegration. Rougher surfaces increase friction, which helps resist early micromotion, and provide a favourable surface for osseointegration [49–51]. Additively manufactured (AM; 3D-printed) components typically have a rougher surface unless post-machined, which can further promote bone ingrowth [50,52]. Beyond this, some implants utilize bioactive coatings such as hydroxyapatite, which act to promote osseointegration by providing a scaffold that mimics natural bone [53]. Second, the loading environment and the mechanical mismatch between implant and bone stiffness affect long-term bone response. As most metallic implants (cobalt-chromium or titanium alloys, approximately 110 GPa) are substantially stiffer than the surrounding cancellous (1-15 GPa) or cortical (10-30 GPa) bone, the implant can carry a disproportionate share of the mechanical load (a phenomenon known as stress shielding) [46,54,55]. This uneven loading limits the mechanical stimulus transferred to the bone that is needed to maintain bone mass and can thus potentially lead to localized bone resorption and, ultimately, aseptic loosening [46,56]. To mitigate this effect, bone-interfacing regions of implants can be engineered with materials having an elastic modulus closer to that of bone, thereby reducing stiffness mismatch at the site of osseointegration [46]. Third, host

bone quality is an important factor for osseointegration, durability, and the likelihood of implant-related complications [57,58]. As the risk of low bone mineral density (BMD) increases with age and is strongly influenced by sex, with postmenopausal estrogen decline accelerating bone loss, a substantial proportion of arthroplasty candidates present with unrecognized osteopenia or osteoporosis [59–61]. For instance, in one report of elderly total hip arthroplasty patients, 18% had osteoporosis and 41% had osteopenia by dual-energy X-ray absorptiometry; female sex and low body mass index were the factors most strongly and negatively associated with BMD [57]. The established relationships between age, sex, and bone density suggest that the biological and mechanical determinants of successful bone ingrowth are not independent of patient demographics, and that sex and age may confound comparisons of fixation methods across patient groups.

Comparative and registry-based evidence on the clinical performance of cemented versus cementless fixation remains mixed. A meta-analysis of survival and clinical function found no difference in the odds of aseptic loosening or in Knee Society Score between fixation methods, with improved survivorship for cemented components when all study designs were pooled together, but equivocal survivorship when the analysis was restricted to randomized trials alone [62]. More recent systematic reviews have described cementless fixation as comparable to cemented in both survivorship and functional outcomes [63], and randomized trials have generally demonstrated non-inferiority of cementless designs [64–66]. However, some studies have reported increased aseptic loosening, primarily in cementless tibial components [67,68]. Although, again, other studies report no difference in aseptic loosening [64,69]. Part of this heterogeneity may reflect design dependence of cementless fixation. Differences in surface roughness, porous coating, or lattice architecture may alter aseptic loosening risk, such that pooled cemented-versus-cementless comparisons may mask design-specific performance [67,69]. To address tibial loosening concerns, a hybrid approach, using a cemented tibial component and cementless femoral component, has also been proposed as a method of drawing on the relative strengths of each fixation method [70].

Registry data add further complexity. An analysis of the Canadian Joint Replacement Registry (CJRR) covering 202,880 primary TKAs performed between 2012 and 2021, of

which only 4.5% were cementless, found no significant difference in adjusted revision risk between fixation methods [71]. Despite the cementless cohort being younger and more predominantly male (both of which are often associated with higher revision risk [72–74]), the findings suggest selection bias favouring cementless fixation among patients perceived as good candidates for a newer technology [71].

International registry comparisons are similarly inconsistent. The New Zealand and Swedish registries have reported inferior outcomes with cementless fixation, the American registry has reported lower revision rates for cementless fixation specifically among men under 65, and the Australian registry has reported improved long-term outcomes for cementless fixation only within posterior-stabilized designs and not other stability categories [75,76].

Despite the apparent equivalence of performance reported in much of this literature, cementless fixation remains disproportionately underused relative to cemented fixation, which continues to be the gold standard of care in most health systems [8,76].

1.2.4 Manufacturers and Model Differences

A small number of multinational manufacturers, primarily DePuy Synthes, Stryker, Zimmer Biomet, and Smith & Nephew, supply the majority of TKA implant systems used internationally, each offering multiple implant families that differ in stability, bearing design, material, and fixation options [77–80]. While the literature has documented outcomes associated with broad design categories, such as cruciate-retaining versus posterior-stabilized stabilization or cemented versus cementless fixation, reporting on the utilization and performance of specific manufacturers and models is comparatively rare, particularly in Canada. Several national and regional registries, including those in the United States, Australia, New Zealand, and the state of Michigan (USA), routinely report implant-level data, including model-specific distributions and revision rates [81–84]. However, comparable Canadian model-level reporting has historically been limited to isolated analyses, such as one recent CJRR-based study that reported aggregate cemented and cementless procedure volumes for four specific implant models between 2012 and 2021 [71].

Successive implant generations from the same manufacturer illustrate how design change occurs incrementally rather than through wholesale replacement. Zimmer's Persona system, introduced in 2012, was built on the platform of the company's earlier NexGen system but incorporated a more anatomically contoured, side-specific tibial component, tighter polyethylene sizing increments, and a shorter tibial keel, changes intended to more closely replicate native knee kinematics [79,85]. A five-year functional comparison of the NexGen and Persona cruciate-retaining systems, performed within the same patients undergoing staged bilateral surgery, found statistically better range of motion, patient-reported outcomes, and anterior knee pain scores with the newer Persona design, which also offered a larger number of femoral, tibial, and patellar sizing options [86]. Similarly, a comparison of Stryker's Triathlon system against its Kinemax Plus predecessor found improved pain relief, function, and patient satisfaction with the newer design at three months, with quality-of-life and satisfaction advantages that persisted to one year [87].

However, not all generational comparisons favour the newer design. A large prospective multicentre study comparing an existing and a newly introduced implant system from the same manufacturer found only small differences in patient-reported outcomes, which, although statistically significant, fell below any recognized minimum clinically important difference, with no significant difference in three-year implant survivorship between the two systems [88]. At the registry level, the Australian Registry has reported that newer knee prosthesis designs do not, as a class, outperform established designs: 29% of evaluated knee replacement models showed higher revision rates than established prostheses, and none of the newer models evaluated showed lower revision rates [89]. A related study found that when a newer prosthesis replaced an older model from the same manufacturer, survivorship improved in only six of eleven such comparisons [90]. Together, the literature suggests that neither manufacturer identity nor product novelty can guarantee improved clinical performance, reinforcing the value of registry surveillance that tracks implant performance at the level of specific manufacturers and models, in addition to broad implant design categories.

1.2.5 Implant Procurement in Canada

Unlike single-payer systems with centralized procurement, medical device purchasing in Canada is decentralized to the hospital or regional health authority level [91,92]. Canadian healthcare funding is predominantly tax-based, but each province is independently responsible for financing and organizing the delivery of health services [91]. With provincial government oversight, individual hospitals and health centres are responsible for both delivering care and purchasing the medical equipment, including joint implants [92]. Hospitals generally pursue one of two purchasing pathways: direct negotiation with a distributor, or participation in a group purchasing organization (GPO), a third-party that negotiates supply contracts on behalf of a pool of member hospitals in exchange for improved pricing and administrative efficiency [92,93]. A 1998 survey of Ontario hospitals found that procurement and implant selection practices varied considerably. Some hospitals negotiated individual contracts with specific suppliers, whereas others participated in block purchasing agreements; surgeons were most often reported as the sole decision-makers for implant design selection; and prices paid for comparable implants varied substantially across institutions, even for the same implant design [94].

In Canada, purchases above CAD $100,000 are subject to a formal, open competitive bidding process under Canada's internal trade agreements, and procurement contracts commonly incorporate risk-sharing arrangements, in which a supplier may be contractually obligated to bear the cost of an early implant failure that necessitates premature revision [92]. This decentralized, hospital-driven model differs from the more centralized tendering systems used in much of Europe, where procurement is typically coordinated by regional bodies of national health systems through competitive tenders intended to prioritize clinical value at the lowest overall price [95]. In Canada, two prominent GPOs include HealthPRO Canada and Mohawk Medbuy, which act as intermediaries for hospital joint-replacement contracts, with many hospitals holding membership in both [96,97]. While GPOs can allow individual hospitals to access more competitive pricing than they could negotiate independently, this consolidation of purchasing power may simultaneously promote more single-supplier markets.

Surgeon-level factors compound these system-level influences on implant choice. Historical US survey evidence found cost and perceived implant quality to be the primary factors influencing surgeon implant selection, though surgeons expressed concern about losing control over that selection as hospital cost-reduction pressures increased [98]. More recent Australian survey data instead found that revision rates, personal familiarity with an implant, and implant quality were prioritized by surgeons, with cost reported to have comparatively little influence, and revision-rate data from joint registries identified as the information surgeons most wanted to see collected and maintained [99]. A scoping review of the sparse literature on implant selection more broadly identified patient anatomy, surgeon familiarity, implant quality, and even the rapport of manufacturer sales representatives as recurring factors in surgeon decision-making [99,100]. Familiarity itself may, however, be self-reinforcing as surgeons often adopt one or two implant systems during fellowship training and continue to use them for much of their subsequent career, a pattern that has been shown to persist as new surgeons adopt the preferences of their supervising surgeons during training [101]. Similarly, operative efficiency may play a role in implant selection, as cementless fixation can shorten operative time by eliminating the need for cement curing [29]. However, the procedure is considered more technically demanding, requiring precise bone cuts to achieve adequate press-fit; thus, these efficiency gains may depend on surgeon experience with the technique [34]. Nevertheless, the increased efficiency may be attractive to surgeons when selecting implants.

Manufacturer influence on implant selection has, in some instances, extended beyond legitimate marketing and sales relationships. The US Department of Justice has fined implant manufacturers, including DePuy Synthes (2023), for paying surgeons undisclosed consulting fees and providing free devices in exchange for using their products, underscoring the potential for financial conflicts of interest to shape implant selection independently of clinical merit [102,103]. Taken together, procurement processes, institutional purchasing power, and surgeon-level familiarity may interact to shape which implants are available to patients in ways that are largely invisible in standard clinical outcome studies but may be observable in registry data that record manufacturer and model at the level of the individual procedure.

1.3 Joint Replacement Outcomes and the Role of Registries

Evaluating the performance of a joint replacement is more complex than a simple binary of success or failure. Outcomes of interest span implant survivorship and revision, complication rates such as infection or periprosthetic fracture, and patient-reported outcome measures (PROMs) capturing pain, function, and satisfaction. No single data source, whether a randomized trial, a single-centre cohort, or an administrative claims database, can efficiently capture all of these outcomes at a population scale, across the full diversity of implants, surgeons, and hospitals in routine use, and over the long follow-up horizons (often a decade or more) relevant to implant survivorship. Arthroplasty registries help to fill this gap by systematically and prospectively recording every primary and revision procedure performed within a jurisdiction, along with the specific prosthesis components used. Registries can thus support population-level surveillance of implant performance, identify epidemiological trends in surgical practice, and, in some cases, flag underperforming implant models earlier than would be possible from individual hospital experience alone.

The scale of registry data is itself a methodological strength. Registries aim for near-complete or complete capture of procedures within a defined population; thus, they are less vulnerable to the volunteer bias, selection bias, and limited statistical power that can affect smaller, single-centre observational studies [104]. This population-level scale is also what makes registries a uniquely suitable, and largely underused, resource for detecting subtle or slow-emerging patterns in implant prescribing, such as the geographic, institutional, and manufacturer-level variation that would be invisible in smaller datasets.

1.4 Joint Replacement Registries

National and regional arthroplasty registries have been established in many health systems. Australia (the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR)), England and Wales (the National Joint Registry), Sweden (the

Swedish Arthroplasty Register (SAR)), the Netherlands (the Dutch Arthroplasty Register, or LROI (Landelijke Registratie Orthopedische Implantaten)), New Zealand, and the United States (the American Joint Replacement Registry (AJRR)) are among the most frequently cited internationally [105,106]. These registries vary in their governance, submission requirements (mandatory versus voluntary), and coverage, but share the common purpose of tracking implant devices, surgical practice patterns, and downstream outcomes over time at a population level [107]. Several registries, including the Dutch LROI, have additionally developed standardized implant classification or reference libraries intended to make implant-level comparisons possible across the many proprietary product names and catalogue numbers used by different manufacturers [108], an approach directly relevant to the implant reference library work described in Chapter 2 of this thesis.

However, registries are not without limitations. Registry data are vulnerable to the same data-quality pressures that affect any large-scale administrative data collection effort, including transcription and coding errors, inconsistent field definitions, missing data, and integration challenges across multiple contributing data sources; this is a globally recognized challenge rather than one specific to any single registry [109–111]. Participation in many registries has historically been voluntary, or mandatory only in a subset of participating jurisdictions; therefore, registries can also be affected by incomplete or non-representative capture of the true underlying population of procedures, a concern discussed in greater detail for the Canadian registry specifically in Section 1.5.3.

1.5 The Canadian Joint Replacement Registry

1.5.1 History, Structure, and Data Sources

The Canadian Joint Replacement Registry (CJRR) was established in 2001 and operates under the Canadian Institute for Health Information (CIHI), Canada's national health information agency, having been developed jointly by CIHI and Canadian orthopedic surgeons [71,112]. Its mandate is to record and analyze clinical, surgical, and prosthesis-level

information on primary and revision hip and knee replacement surgeries performed across Canada, with the goal of supporting improvements in the quality of care and clinical outcomes for joint replacement recipients [113].

Participation in the CJRR has historically been voluntary, though a subset of provinces now require mandatory submission, and this heterogeneity in participation status across jurisdictions is one of the defining structural features of the registry, addressed further in Section 1.5.3 [4,114]. As of 2025, data may be submitted to the CJRR through three electronic pathways: a legacy CJRR-specific electronic file system, the Discharge Abstract Database (DAD), which primarily captures inpatient hospitalizations, and the National Ambulatory Care Reporting System (NACRS), which captures ambulatory, emergency, and same-day surgical care [115,116]. Paper-based forms and an earlier web-based submission tool have since been retired (2013 and 2019, respectively) in favour of these electronic pathways [116]. Regardless of pathway, hospitals have 1 year to submit their records [113]. Submitted records are then subject to automated validation checks, for example flagging blank mandatory fields, invalid field lengths, and out-of-range values, and providers receive a report identifying any records rejected for correction and resubmission [113]. Accepted records are then de-identified before being made available for analysis. Approved third-party health information software (such as MED2020's WinRecs [117]) supports data entry either manually or via barcode scanning of the barcodes typically present on prosthesis and cement packaging, an approach the CJRR recommends over manual transcription specifically to reduce transcription error [117,118].

Early analyses of CJRR data documented substantial interprovincial variation in both age-adjusted arthroplasty rates and specific implant category utilization that could not be fully explained by underlying differences in patient demographics. Age-adjusted TKA rates for women varied by more than 100% between the same two provinces, and eastern provinces generally showed lower rates of UKA use than western provinces [114]. This same early period of CJRR reporting found that women had substantially higher age-adjusted rates of TKA than men (148 versus 110 per relevant population unit) and accounted for approximately 61% of TKA recipients, and that the largest increases in TKA utilization over time occurred among patients aged 45 to 65 [114]. This combination of unexplained

geographic variation and a persistent sex disparity in utilization is a recurring theme that supports the analytic approaches, in particular the sex-disaggregated clustering analysis, described in Section 1.6.2.

1.5.2 Variables Collected: The Minimum Data Set

The CJRR defines a formal Minimum Data Set (MDS) specifying the fields required (or optionally collected) for every knee and hip replacement record, along with each field's length, mandatory or optional status, valid values, and applicable joint type [113]. The MDS is organized into sections covering record information (a unique record identifier, record type, fiscal year, hospital province, and submission type), surgeon demographics (surgeon identifier and name), patient demographics (patient identifiers, health card information, birth date, sex, postal code, hospital identifier, and surgery date), and general procedure information (surgical side, type of replacement, type of primary procedure, diagnosis grouping, and, for revisions, reason for revision) [113]. For knee replacements specifically, prosthesis information is collected separately for the femoral component, tibial component, tibial insert, and patellar component, recording, for each, the manufacturer (an "other" manufacturer field for entries outside the standard pick-list), the product number, and the lot number, along with corresponding fields for the cement product used [113]. This component-level granularity is what makes the CJRR valuable for manufacturer-, model-, and design-level analyses, yet this data is largely underused. Luckily, questions relevant to these features are addressed elsewhere in this thesis.

It should be noted, however, that the current minimum dataset was reduced from what was previously collected. Prior to 2012 (when the current minimum dataset was adopted), additional details such as surgical approach, PCL management, surgery wait times, and deep vein thrombosis preventative agents used were also collected [119–121]. The current, reduced MDS was implemented aiming to improve surgeon participation and CJRR coverage while still aligning with the minimum elements recommended by the International Society of Arthroplasty Registries [120]. Both the current and past data collection forms are available in Section A.1.

One important structural limitation for all analyses in this thesis is that, while persistent patient identifiers are available from CJRR with appropriate data linking, they were not provided in this data request due to constraints of their Graduate Student Data Access Program. Therefore, individual procedures cannot be definitively linked back to the same patient. This is particularly consequential for bilateral TKA, in which the same patient may undergo two separate procedures, on the same or different surgery dates, that appear in the analytic dataset as two independent, unlinked records rather than as a single patient's. This limitation is revisited in Section 1.6.1 in the context of the statistical assumptions required for registry-based analysis.

1.5.3 Reporting Rates and Coverage

CJRR participation has historically combined mandatory and voluntary submission across provinces; thus, reporting completeness has varied by jurisdiction and year. CIHI-reported percentage coverage rates for primary hip and knee replacement submissions from 2019 through 2023 are summarized in Table 1.1. Provinces with mandatory CJRR submission requirements, indicated with an asterisk, generally report coverage approaching or exceeding 90%, while several voluntary-reporting jurisdictions show much lower reporting rates. Notably, New Brunswick and Quebec report quite low coverage throughout the period. National coverage across all reporting jurisdictions ranged from approximately 68% to 74% over 2019-2023 [3,4].

Table 1.1: CJRR percentage coverage by jurisdiction, 2019-2023 [3,4]. *Provinces with mandatory CJRR submission.

Jurisdiction	**2019**	**2020**	**2021**	**2022**	**2023**
Newfoundland and Labrador	99.6	99.0	99.0	98.8	99.4
Prince Edward Island	—	n/a	n/a	n/a	n/a
Nova Scotia*	94.8	93.8	92.9	94.6	94.4
New Brunswick	10.4	8.1	11.0	8.3	6.5

Table 1.1: CJRR percentage coverage by jurisdiction, 2019-2023 [3,4]. *Provinces with mandatory CJRR submission.

Jurisdiction	**2019**	**2020**	**2021**	**2022**	**2023**
Quebec	1.9	0.4	0.6	2.3	2.2
Ontario*	95.8	91.8	84.8	91.9	93.8
Manitoba*	99.7	99.8	99.2	99.6	99.4
Saskatchewan	90.0	90.6	99.6	99.9	99.8
Alberta	80.8	76.3	74.7	72.4	74.2
British Columbia*	88.4	97.2	95.6	95.0	86.9
Yukon	—	—	n/a	n/a	n/a
Northwest Territories	97.8	98.6	98.5	90.2	100.0
Canada	73.4	73.9	68.2	72.4	72.1

This uneven coverage has methodological consequences for CJRR-based research. To limit bias arising from systematically incomplete reporting, published analyses commonly restrict their study population to provinces and territories with either mandatory submission or a minimum coverage threshold, often 70% or higher [71]. This approach reduces (though does not eliminate) the risk that low-reporting jurisdictions bias national estimates, but it does so at a direct cost to generalizability as findings from such a restricted cohort more accurately describe a provincial or regional subset of Canadian practice than the country as a whole, and jurisdictions with chronically low reporting, notably Quebec and New Brunswick, are effectively excluded from most published CJRR analyses, including those conducted for this thesis.

1.6 Analytic Approaches in Registry Research

1.6.1 Statistical Methods and Their Limitations

Registry-based studies of implant prescribing and outcomes typically rely on a common set of statistical tools including descriptive summary statistics; Pearson's chi-squared tests of independence and tests for trend, such as the Cochran-Armitage test, for assessing changes in categorical proportions (for example, manufacturer market share) across provinces or over time; linear and logistic regression for adjusted comparisons across patient and procedure characteristics; and, where revision data are available, survival analysis for estimating cumulative revision risk. These approaches are well suited to the scale of registry data but carry limitations that follow from the structure of the underlying dataset. As noted in Section 1.5.2, the absence of a persistent patient identifier in CJRR data of this thesis means that bilateral procedures cannot be linked to a single patient, so standard regression and survival models, which typically assume that observations are statistically independent, must be interpreted with the understanding that a subset of records may in fact represent non-independent observations from the same individual. However, one investigation into the effect of not accounting for bilaterality in revision risk estimation, assuming all observations were independent, reported minimal effects and concluded that analyses can generally be conducted without accounting for subject dependency [122].

A second, related limitation concerns the non-random allocation of treatment inherent in observational registry data. Unlike a randomized controlled trial, in which fixation method, implant model, or design category is assigned by protocol, registry data reflect real-world clinical decision-making, so researchers cannot control which patients receive which implants. This produces substantial imbalance in exposure groups; for example, cementless fixation accounted for only a small minority of TKAs relative to cemented fixation in the CJRR cohort analyzed by Chen et al. (2025), and, as discussed in Section 1.2.3, these imbalanced groups often differ systematically on factors such as age and sex that may independently predict outcomes. This combination of non-random treatment assignment and observable (and likely unobservable) confounding is a central methodological challenge

for any registry-based comparison of implant types, fixation methods, or manufacturers, and underscores the need for careful attention to confounding adjustment, as demonstrated throughout this thesis.

1.6.2 Clustering and Unsupervised Learning

Overview of Clustering

Clustering is an unsupervised statistical technique. Unlike regression or classification, it does not require pre-existing outcome labels, but instead groups observations so that members of the same cluster are more similar to one another, and more dissimilar to members of other clusters, according to some defined distance or dissimilarity metric [123]. In health services research, clustering has been used to identify latent subgroups of patients, providers, or institutions from prescribing or treatment data that would not be apparent using traditional regression-based approaches, which typically model one outcome as a function of predictors specified in advance rather than searching for structure across many variables simultaneously [124]. Applications of unsupervised clustering to health record and registry data have proven effective at recovering clinically coherent subgroups in other domains, including comorbidity clusters in rheumatoid arthritis [125], clinical subtypes of Alzheimer's disease [126], composite phenotypes in sepsis [127], multimorbidity patterns using k-means [128], and clinical phenotypes among patients hospitalized with COVID-19 [129]. Comparatively little of this work, however, has been extended to device- or prescribing-level data such as prosthesis component selection.

One challenge for clustering component-level registry data is that healthcare datasets typically combine continuous variables (such as patient age) with categorical variables (such as implant manufacturer or fixation type). Conventional clustering algorithms such as k-means are not well suited to this mixture, because computing a single, meaningful similarity measure across variable types is non-trivial, as it is often unclear whether continuous and categorical distances are capturing comparable ideas of "similarity," or whether the two are even on comparable scales [123]. Gower distance is the most widely used solution to

this problem [130]. It computes a composite dissimilarity measure in which continuous variables are scored using the normalized absolute difference between two observations (scaled by that variable's overall range), while categorical variables are scored as a simple binary match or mismatch, with the final distance calculated as an average, optionally weighted, across all included variables [130]. A recognized limitation of the conventional Gower distance is that categorical variables can disproportionately influence the resulting distance metric, since a categorical mismatch immediately reaches the maximum possible distance for that variable, whereas a continuous variable only reaches its maximum distance when comparing the two most extreme values in the dataset. Modified approaches that substitute the interquartile range for the full range when scaling continuous variables have been proposed to help rebalance this asymmetry [131].

Since the procedure-level dataset combines categorical (nominal) and continuous variables, clustering methods that natively accommodate mixed-type data were prioritized over approaches that require categorical variables to be forced into a Euclidean-distance framework via one-hot encoding [130–132]. Several algorithmic families, described in the clustering manuscript of this thesis (Chapter 6), were run in parallel, rather than relying on a single method, following the recommendation of recent clustering methodology reviews, which note that no single algorithm dominates across health applications and that agreement across methods strengthens confidence that identified structure reflects the data rather than the assumptions of any one algorithm [125,133,134].

Cluster stability was assessed via bootstrap resampling using the Jaccard coefficient, following established thresholds in which a mean Jaccard similarity above 0.75 indicates a stable cluster and above 0.85 a highly stable cluster [128,135]. Agreement across the four clustering methods was evaluated by computing Gower-distance silhouette scores uniformly across each method's final solution, allowing internal validity to be compared on a like-for-like basis despite the differing assumptions underlying each algorithm. Information-theoretic measures, including entropy and mutual information, can also be used to quantify how strongly individual variables contribute to the resulting cluster structure [131]. Where two independent clustering solutions need to be compared directly, the Adjusted Rand Index (ARI) provided a chance-corrected measure of agreement between the two

partitions, with published simulation-based guidelines suggesting that ARI values above approximately 0.90, 0.80, and 0.65 correspond to excellent, good, and fair cluster recovery respectively, and values below 0.65 indicating poor agreement [136,137]. Adjusted Mutual Information (AMI) offers a related, information-theoretic alternative that is less sensitive than ARI to imbalance in cluster sizes [136,138].

Applying Clustering to TKA Implant Prescribing

Implant selection in TKA reflects a mixture of clinical, institutional, and surgeon-level influences, as described throughout Chapter 1, yet it has typically been studied one attribute or one institutional factor at a time, and is more often treated as a fixed input to be adjusted for when studying downstream clinical outcomes than as an outcome of interest on its own. This is despite well-documented evidence of substantial, and only partially explained, variation in implant prescribing. Early CJRR analyses found more than two-fold interprovincial differences in age-adjusted TKA rates and in the use of specific implant categories that could not be attributed to patient demographics alone [114], and surgeon-level survey evidence has found that implant choice is shaped as much by individual preference, training background, and brand familiarity as by patient-specific clinical indications, with North American surgeons reporting the use of fewer than two distinct knee implant brands in a typical year and identifying anticipated outcome improvement and product cost, rather than patient characteristics, as their dominant reasons for switching systems [98]. More recent work has linked implant selection to surgeon-level factors such as fellowship training, years in practice, and adoption of robotic-assisted surgical techniques, reinforcing that prescribing behaviour in TKA is not uniform across the specialty and is only partially explained by clinical indication alone [139].

This variation carries an equity dimension as well as a clinical and health-systems one. Registry-based work has shown that women and men experience different rates of TKA utilization and, potentially, different revision risk profiles [4,114] and that race, ethnicity, and sex are more broadly associated with differences in TKA access and outcomes [140]. Lower socioeconomic status has independently been linked to lower rates of joint replace-

ment for osteoarthritis, suggesting that structural, rather than purely clinical, factors help determine who receives surgical care [141]. If implant selection itself, not merely the decision to operate, varies systematically by patient demographics independent of clinical indication, this would represent a distinct and comparatively under-examined dimension of potential inequity in TKA care. The clustering analysis in this thesis thus aims to investigate whether patient factors are associated with implant prescribing patterns.

1.7 Purpose and Overview of the Thesis

1.7.1 Rationale and Gaps Addressed

The literature reviewed above identified several gaps that this thesis aimed to address. First, Canadian-specific evidence on implant prescribing is comparatively sparse relative to international registries such as the AOANJRR or National Joint Registry, despite clear evidence of interprovincial and institutional heterogeneity in Canadian arthroplasty practice. Second, existing Canadian and international literature has generally examined implant selection one factor at a time, whether patient-level (age, sex), design-level (fixation, stability), or system-level (procurement, hospital type), rather than as a multidimensional outcome shaped by all of these factors simultaneously. Third, and most directly relevant to this thesis's methodological contribution, clustering and other unsupervised approaches remain underused in arthroplasty registry research relative to standard regression and survival analysis, despite evidence from other clinical domains that such methods can reveal latent structure invisible to traditional approaches. Fourth, data quality and standardization challenges, including inconsistent implant naming across manufacturers, catalogue numbers, and submission pathways, limit the reliability of manufacturer- and model-level analyses using CJRR data as currently structured; this thesis addressed this gap directly through the development of a dedicated implant reference library.

1.7.2 Objectives

To address these gaps, this thesis had four broad objectives: (1) to develop and evaluate data-quality tools, including a standardized implant reference library and supporting validation logic, to improve the reliability of manufacturer- and model-level CJRR analyses; (2) to characterize national and provincial trends in TKA fixation method (cemented versus cementless), in patellar resurfacing and implant stability (cruciate-retaining versus posterior-stabilized) practices, and in implant manufacturer and model utilization within the CJRR, and, where appropriate, to compare these trends to those reported by other national arthroplasty registries; and (3) to apply clustering methods to CJRR prosthesis data to identify latent implant prescribing subgroups and to evaluate whether patient demographic and institutional factors predict cluster membership.

1.7.3 Hypotheses

In light of the literature on registry data quality and the current processes of the CJRR, it was hypothesized that the open-source implant reference library, applied retrospectively, would improve missing and misclassified data in the CJRR dataset used in this thesis. Consistent with international trends and the growing body of literature supporting the clinical efficacy of cementless fixation, cementless TKA utilization in Canada was hypothesized to have increased significantly over the study period, with younger and male patients more likely to receive cementless implants. In consideration of previous Canadian and international registry reports on patellar resurfacing trends and PCL management, it was hypothesized that both patellar resurfacing and insert stability design would differ by province and over the study period, and that patellar resurfacing would be more common among posterior stabilized procedures. Given the decentralized structure of Canadian medical device procurement and its consequent distribution of institutional purchasing contracts, substantial provincial and institutional variation in implant manufacturer, model, fixation method, and stability design was expected. It was further hypothesized that CJRR prosthesis data would resolve into a small number of interpretable implant prescribing archetypes under clustering analysis, and that these archetypes would be predicted, at

least in part, by patient age, sex, province, and procedure year, independent of overall procedure volume.

1.7.4 Approach

This thesis used de-identified, record-level CJRR data obtained through CIHI's Graduate Student Data Access Program, covering primary TKA procedures performed across participating Canadian jurisdictions. Consistent with the reporting-coverage considerations discussed in Section 1.5.3, analyses were restricted to provinces and territories with mandatory CJRR submission or above a 70% reporting threshold. Data quality tools, including an open-source implant reference library linking manufacturer catalogue numbers to standardized component attributes, were developed to support these analyses and improve the reliability of manufacturer- and model-level reporting from CJRR data more broadly. Descriptive and inferential statistical methods, including trend tests, regression, and market concentration measures, were used to characterize fixation, patellar resurfacing and insert stability, manufacturer, and model trends over time and across jurisdictions. Finally, mixed-data clustering methods, applied to component-level prosthesis records, were used to identify implant prescribing archetypes described in Section 1.6.2.

1.8 Thesis Structure

This thesis comprises five distinct manuscripts, each to be read as a stand-alone paper. As such, background or methodological information may be repeated throughout these documents. The first study describes the application of a retrospective data quality tool developed using open-source medical device databases (Chapter 2). This tool is used in all the following studies to supplement the implant characteristic data provided by the CJRR. Subsequent studies cover fixation trends, focusing on tibial baseplate fixation methods, including which models are primarily used within each fixation method (Chapter 3); patellar resurfacing and insert stability design trends, which characterize the rates of patellar resurfacing in combination with different stability designs to investigate whether these surgical

decisions may be associated ((Chapter 4); implant market trends, which characterize, at a more granular level, manufacturer and model utilization at the national and provincial levels, and are segregated by fixation method and insert stability (Chapter 5); and, finally, the clustering analysis, which assesses overall TKA configuration patterns (Chapter 6). You may note slightly different sample sizes across these studies due to differences in data missingness of the relevant variables. The thesis concludes with Conclusions and Recommendations (Chapter 7), in which final thoughts, experiences, and recommendations are presented.

Chapter 2

Data Quality and the Implant Reference Library

2.1 Abstract

Joint replacement registries such as the Canadian Joint Replacement Registry (CJRR) depend on accurate implant-level data, but data quality issues, including transcription errors, inconsistent variable definitions, and incomplete linkage to third-party databases such as the International Prostheses Library (IPL), which houses implant model details, limit the reliability of registry-based analyses. This study developed an open-source, independently constructed reference library for Canadian total knee arthroplasty (TKA) devices and evaluated whether it could be applied to, and improve, existing CJRR implant-level data. The library was built from FDA, Health Canada, and manufacturer sources through an eleven-stage pipeline and comprised 29,791 unique catalogue number records, with applicability-matrix-aware missingness across design, material, and dimensional fields averaging 70.4%. Linking the library to 793,508 CJRR component-level records by catalogue number matched 95.8% of rows, filled 768,603 previously missing field values, and identified numerous instances of disagreement with existing CJRR/IPL-derived fields, including substantial disagreement in component type and model name labelling. Catalogue-number

cleaning and Global Trade Item Number (GTIN) substring recovery further resolved a subset of the 56,533 previously unmapped records. These findings support the hypothesis that a standardized, open-source implant library can identify and correct data errors in the CJRR, improving the reliability of implant-level registry analyses, while also revealing specific, addressable gaps, including inconsistent variable naming, incomplete minimum data set elements, and reliance on submission-time validation alone, that limit current CJRR data quality. Adoption of an open-source implant reference library, standardized minimum data set elements, and real-time validation processes modelled on other national registries are proposed as concrete steps toward addressing these gaps.

2.2 Introduction

Joint registries aim to capture population-level data on surgical procedures, including patient demographics and prosthesis characteristics, to enable surveillance of implant performance, identify epidemiological trends, and inform healthcare practices. The Canadian Joint Replacement Registry (CJRR), established in 2001, functions under the Canadian Institute for Health Information (CIHI) to collect and analyze hip and knee arthroplasty data across Canada, with many provinces requiring mandatory registry submission [1]. The value of this registry is notwithstanding; numerous research articles, registry reports, and public health guidelines have been published, extracting health insights from registry data to improve patient care [2–5].

However, such large data collection projects are not without their challenges. While registry data have great potential to improve healthcare practices, they are also vulnerable to data quality issues, including transcription errors, coding errors, variable definitions, integration across multiple data sources, and incomplete data. The CJRR is not unique in this struggle; data quality is a globally reported challenge among registries [6–12].

However, several of these challenges are specific to the CJRR's current data collection and validation processes. Data are submitted through multiple pathways, including a legacy electronic file system and abstraction from hospital discharge databases, and the

national reporting rate has averaged only 73% since 2018, varying substantially by jurisdiction (Section B.1). Existing automatic validation checks confirm that submitted fields are present and correctly formatted but do not verify that a submitted implant identifier corresponds to a genuine, correctly classified device, leaving component misclassification, inconsistent variable naming, and incomplete catalogue-number linkage to the IPL largely undetected at the point of submission (Sections B.1 and B.2).

By contrast, several international joint registries, including the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR), the Dutch Arthroplasty Register (LROI), and the National Joint Registry (NJR) of England, Wales, Northern Ireland and the Isle of Man, have adopted more active quality assurance measures, including mandated participation, real-time predictive validation, and structured, bidirectional auditing against hospital and administrative records, achieving higher completeness and reliability than submission-time edit checks alone [13–16] (Section B.1.4).

Building on these observations, this study aimed to determine whether an independently constructed, open-source implant reference library can be applied to, and improve, existing CJRR implant-level data. This article examines the specific data quality challenges within the CJRR, proposes potential quality assurance solutions, and presents the development of an implant reference library as a scalable, open-source quality control tool to improve data accuracy, completeness, and research reliability. The approach is informed both by the existing literature and by the author's experience working with CJRR's primary total knee replacement data. It is hypothesized that a standardized, open-source implant library can identify and correct data errors, enabling more reliable registry-based analyses and subsequently derived clinical recommendations.

2.3 Methods

2.3.1 Data Sources

Two primary data sources were used: the CJRR-provided dataset and the developed open-source implant reference library.

CJRR component-level records used for this analysis (793,508 rows) were derived from the CJRR's existing linkage to CIHI's International Prostheses Library (IPL); the CJRR's data submission pathways, jurisdictional coverage, and existing quality assurance practices are described in Section B.1. Prior to any library linkage, CJRR/IPL-derived implant characteristic fields exhibited substantial missingness, driven by a combination of incomplete catalogue-number matching to the IPL and structural gaps within the IPL itself; these patterns varied by submission stream and component type and are described in full in Sections B.2.4 and B.2.5.

The open-source implant reference library was constructed independently from multiple regulatory and manufacturer sources, including the FDA Global Unique Device Identification Database (GUDID), Health Canada's Medical Devices Active Licence Listing (MDALL), Global Medical Device Nomenclature (GMDN) terms, manufacturer electronic Instructions for Use (eIFU) documents, supplemental manufacturer dimension references, and a New Zealand medical device registry extract; full source descriptions and the resulting data elements are provided in Section B.3.

Briefly, the open-source reference library was built through an eleven-stage, re-executable Python pipeline that merged and cross-validated the above sources by GTIN, catalogue number (VERSION_MODEL_NUMBER), and GMDN-derived component classification, supplemented by manufacturer-specific parsing of eIFU material composition tables and a structured manual review workflow for records that could not be auto-populated from any source (Section B.3.4). Each resulting record was assigned a component_type, applicable design, material, and dimensional fields per a pre-specified applicability matrix (Table B.3; Section B.3.3), and pipeline metadata, including data_source, match_type (exact, normalized, or unmatched GUDID-MDALL linkage), confidence_score (the fraction of applicable

fields populated), and a needs_review flag.

Table 2.1: Component Field Applicability Matrix

Field	**Applicable Component Types**	**Not Applicable**
stability	Femoral, Insert, TKA System	Tibial, Patellar, Stem
mobility	Insert	All others
fixation	Femoral, Tibial, TKA System	Insert, Patellar, Stem
design_fixation_surface	Femoral, Tibial, Patellar	Insert, Stem
design_articular_surface	Femoral, Insert	Tibial, Patellar, Stem
ap_length (medial and lateral)	Femoral, Tibial	Insert, Patellar, Stem
ml_width	Tibial	All others
diameter	Patellar, Femoral Stem, Tibial Stem, Stem	Femoral, Tibial, Insert
thickness	Insert	All others
metal_material	Femoral, Tibial, Patellar	Insert, Stem
poly_material	Insert, Patellar	Femoral, Tibial, Stem
antioxidant	Insert	All others
surface_treatment	Femoral, Tibial	Insert, Patellar, Stem

Similar to the CJRR/IPL missingness, an analogous, independently sourced pattern of missingness existed within the open-source reference library itself. The completed open-source implant reference library comprised 29,791 records, each corresponding to a unique catalogue number. Records were distributed unevenly across component types:

Insert (15,429; 51.8%), Femoral (5,052; 17.0%), Tibial (3,406; 11.4%), Stem (1,332; 4.5%), Femoral Stem (976; 3.3%), Patellar (776; 2.6%), Monoblock Tibial (511; 1.7%), and Tibial Stem (165; 0.6%). A further 2,136 records (7.2%) could not be assigned a component type by the classification pipeline, and 8 records (<0.1%) were classified as a Hip Prosthesis despite the library's targeted scope of Canadian TKA devices, indicating a small number of records not removed by the keyword-based exclusion filtering applied during library construction. These records were removed from the library after manual inspection.

Applying the field applicability matrix (Table B.3) to the design, material, and dimensional fields listed resulted in 146,980 applicable field-record combinations across the library, of which 103,416 (70.8%) remained missing following the full construction pipeline. Missingness varied substantially by field (Table 2.2): fixation had the lowest missingness, while design_fixation_surface, surface_treatment, and antioxidant had the highest.

Table 2.2: Open-source implant library completeness by field (n = 29,791; applicability per Table B.3).

Field	Applicable Component Types	N Applicable	N Missing	% Missing
design_fixation_surface	Femoral, Tibial, Patellar	9,234	8,702	94.24
surface_treatment	Femoral, Tibial	8,458	7,918	93.62
antioxidant	Insert	15,429	14,203	92.05
ap_lateral	Femoral, Tibial	8,458	7,389	87.36
ap_medial	Femoral, Tibial	8,458	7,389	87.36
ml_width	Tibial	3,406	2,915	85.58
metal_material	Femoral, Tibial, Patellar	9,234	7,885	85.39
diameter	Patellar, Femoral Stem, Tibial Stem, Stem	3,249	2,724	83.84

Field	Applicable Component Types	N Applicable	N Missing	% Missing
bearing_type (mobility)	Insert	15,429	11,533	74.75
design_articular_surface	Femoral, Insert	20,481	15,085	73.65
poly_material	Insert, Patellar	16,205	11,426	70.51
thickness	Insert	15,429	7,394	47.92
stability	Femoral, Insert	20,481	9,033	44.1
fixation	Femoral, Tibial	8,458	1,353	16
Overall		**146,980**	**103,416**	**70.36**

The pipeline-level indicators suggested substantial variability in record completeness. The mean confidence_score (the fraction of applicable fields populated per record) was 0.460 (median 0.474), and no record in the library achieved a confidence_score of 1.0. Consistent with this, 26,891 records (90.3%) were flagged for manual review. The match_type field, which reflects whether a record's GUDID and MDALL source entries were linked during the merge stage (Section B.3.2, Section B.3.3), showed that 71.1% of records were unmatched between the two sources (i.e., sourced from only one of GUDID or MDALL), 27.5% matched exactly, and 1.4% matched only after normalization. This pattern was broadly consistent with the underlying source composition. The FDA GUDID alone contributed 48.8% of records, MDALL alone 18.9%, and the two sources jointly accounted for the remaining 32.3%.

2.3.2 Linkage to CJRR Data and Recovery of Unmapped Catalogue Numbers

The reference library was linked to CJRR component-level records by catalogue number. Records that did not match on an initial exact join were re-attempted after removing punctuation and underscore characters from the catalogue number field, since preliminary

review indicated that a subset of non-matches reflected minor formatting inconsistencies rather than true absence from the library. For catalogue numbers that remained unmapped after cleaning, an observation that some unmapped entries resembled a full unique device identifier (UDI) rather than a bare catalogue number motivated an additional recovery check. UDI codes generally include two segments: a fixed device identifier (often containing the GTIN) and a variable production identifier that includes manufacturing information such as lot and serial numbers [17]. Unmapped catalogue numbers were therefore tested for whether they contained an embedded, valid GTIN as a substring that could be linked to a corresponding library record's device_id and catalogue_number fields. However, because UDI production identifiers can in principle contain more than one embedded GTIN substring, and a single GTIN can be embedded in more than one UDI string, this check was treated as a probable rather than certain match. Unmapped catalogue numbers were separately checked for whether the same string had a successful match elsewhere in the dataset, to distinguish catalogue numbers genuinely absent from the library from those affected by within-dataset transcription inconsistency.

2.3.3 CJRR Data Quality and Congruency Analyses

In the CJRR/IPL data, agreement between the submitter-entered JOINT_COMP field and the IPL-derived ComponentType field was assessed by cross-tabulation by component type (Section B.2.6). Manufacturer and model-name reliability were assessed by grouping matched records by catalogue number and counting the number of distinct manufacturer/model-name combinations associated with each; catalogue numbers associated with more than one manufacturer or model-name combination were flagged as a probable data entry or classification error (Section B.2.6). Duplicate component-type submissions and component-set completeness were assessed at the joint-record level (Sections B.2.7 and B.2.8). Provincial differences in unmapped catalogue number rates were tested using a Pearson's chi-squared test of independence (Section B.2.9).

2.4 Results

Despite the relatively low completeness reported above, the open-source library still substantially contributed to the CJRR data. The resulting open-source reference library was linked to the CJRR IPL (793,508 records) by catalogue number. Of these, 759,804 records (95.8%) matched a corresponding library entry, while 33,704 records (4.2%) had no library match at all. At the level of unique catalogue numbers, the overlap between the two sources was more modest: 4,422 unique catalogue numbers were present in both datasets, 10,447 were present only in the CJRR submissions, and 25,253 were present only in the library (i.e., licensed devices not observed among CJRR submissions in this dataset).

For the matched records, the pipeline updated values across 32 processed fields. In total, the open-source library filled 768,603 values (i.e. populated previously blank cells in fields that already existed in the CJRR dataset), including Size (267,667 values), MMat (114,443), PMat (61,347), Thick (42,514), ModelName (37,863), ComponentType (37,655), Diameter (35,818), Stability (26,450), and smaller counts for the AP and ML dimension fields, Mobility, and Fixation.

A further 2,417,021 values differed between the open-source library and the pre-existing CJRR/IPL-derived fields for the same record. The largest discrepancies were concentrated in component type (722,101 of 759,804 matched records, 95.0%) and model name (491,223 records, 64.6%), followed by size (353,838), stability (299,197), metal material (143,133), polyethylene material (123,684), the AP dimension fields (82,893 each, medial and lateral), ML (79,107), fixation (32,886), mobility (3,897), and manufacturer name (2,150).

The library additionally provided a mechanism for recovering some of the 56,533 records (7.1% of the dataset) that remained without a mapped model name after standard linkage. Applying additional catalogue number cleaning (removing punctuation and underscore characters) recovered matches for 1,470 unique previously unmapped catalogue numbers against the reference library, compared with 605 recovered against the IPL under the same cleaning rule.

The additional GTIN-substring recovery check identified 4,814 unmapped records (8.5% of the 56,533) with at least one embedded GTIN match; 265 GTINs were matched by more

than one unmapped catalogue number, and 40 unmapped catalogue numbers matched more than one GTIN. Separately, 598 of the 11,003 unique unmapped catalogue numbers (5.4%) were found to be successfully matched elsewhere in the dataset.

2.5 Discussion

This study demonstrated that an open-source, independently constructed implant reference library could substantially improve the quality and usability of CJRR registry data. This scale of enrichment and cross-validation is not currently achievable through the CJRR's existing linkage to the proprietary IPL alone, since the CIHI/CJRR/IPL provides no mechanism for external researchers to verify, correct, or supplement the fields derived from the IPL.

Linking the library to CJRR records matched 95.8% of component-level rows, though the overlap was much lower at the level of unique catalogue numbers (4,422 shared between the two sources, against 10,447 unique to the CJRR submissions and 25,253 unique to the library). This disproportion may reflect the concentration of implant utilization as a relatively small number of catalogue numbers account for most implants used in practice, so the 4,422 shared catalogue numbers alone covered nearly all matched records, while the 10,447 CJRR-only catalogue numbers were, collectively, rarely used. At least some of these CJRR-only catalogue numbers likely correspond to the invalid or malformed unmapped catalogue number submissions rather than to legitimate devices absent from the library. The catalogue-number cleaning and GTIN-substring recovery analyses offer partial support for this, having recovered matches for a subset of previously unmapped entries once formatting issues were corrected.

The library also meaningfully reduced missingness for applicable implant characteristic fields identified as poorly captured through existing CJRR/IPL linkage (Figs. B.4 and B.5). Particular improvement was noted in the material and size fields. This improvement may have important implications for research, as fields that previously limited the sample size of usable records may now pose less of a constraint, allowing these variables to be incorporated

into a broader range of analyses.

Using the reference library as an independent, standardized point of comparison allowed further quantification of the classification issues discussed previously. The library-derived MANUFACTURER_NAME_STD field disagreed with the existing standardized manufacturer field in 2,150 matched records, indicating a low but measurable rate of manufacturer misattribution, likely arising from barcode scanning of an incorrect label or incorrect manufacturer selection in data entry. Disagreement was more extensive for ComponentType and ModelName discrepancies (95.0 and 64.6% of matched records, respectively). This suggests that submitter- and IPL-derived component and model labels cannot be used uncritically. Given that these two fields already exhibit the labelling inconsistencies (e.g., "Knee Femoral Component" vs. "Femoral"; inconsistent hyphenation and capitalization of model names), a substantial share of this disagreement likely reflects differences in naming convention between the CJRR/IPL and the open-source reference library rather than genuine misclassification. However, this is unlikely to fully explain the reported discrepancies. The JOINT_COMP-ComponentType congruency mismatches reported in Section B.2.6, particularly for tibial components, indicated that some proportion of the ComponentType disagreement reflects true classification errors that the reference library corrected rather than naming convention noise. Disentangling these two sources of disagreement was beyond the scope of the current pipeline, but the scale of the discrepancy nonetheless underscores the value of an independently constructed, standardized library as a cross-check on registry-derived classification fields

The noted lack of a standardized naming convention has, as described above, posed substantial challenges for the data usability reliability. This strongly suggests that standardized variable definitions and naming conventions at the point of data collection or IPL curation would be invaluable to improving the data quality.

Additionally, the choice of which field (ComponentType or JOINT_COMP) to treat as authoritative for component classification may also have downstream effects. As reported above, it affects how components are counted and characterized, particularly for tibial components. The prevalence of this issue is consistent with the broader international experience wherein registries with active, structured validation and audit programs, such

as the AOANJRR, LROI, and NJR, achieve higher data completeness and reliability than registries primarily relying on submission-time edit checks alone (like the CJRR). The fact that this open-source library, as a retrospective, external validation layer applied after data collection, could reproduce some of the benefit of these real-time validation systems is encouraging. However, real-time implementation would prevent such errors from entering the registry to begin with rather than requiring after-the-fact reconciliation.

Beyond filling gaps in already-collected fields, the open-source library meaningfully improved the granularity of implant characteristic data available for analysis. Several fields introduced distinctions that did not previously exist in the CJRR data. For example, stability values that had previously been grouped together, (e.g. medial-pivot, anterior-stabilized, and cruciate-retaining insert designs were grouped as "Minimally Stabilized (CR)" in the CJRR/IPL) are now differentiated, and poly_material now distinguishes standard UHMWPE from cross-linked and highly cross-linked polyethylene, as well as antibiotic-loaded polyethylene, using consistent terminology not previously available in the CJRR/IPL fields. Fields such as implant stability (constraint level), metal and polyethylene material composition, antioxidant (Vitamin E) stabilization, and surface treatment, identified as having substantial missingness, were also populated for thousands of additional records. This additional granularity may have important implications for research. Distinguishing, for example, cruciate-retaining from posterior-stabilized or medial pivot constrained inserts, or standard from vitamin-E-stabilized polyethylene, may be relevant to survivorship and revision-risk analyses that would otherwise have to exclude these records, completely exclude these variables due to sample size constraints, or rely on coarser, CJRR-native categories.

The library also functioned as a tool for identifying, and in some cases recovering from, data entry mistakes rather than simply supplementing missing fields. The additional catalogue number cleaning and GTIN-substring analysis suggested that a fraction of the 56,533 unmapped records reflect recoverable data entry or formatting issues, rather than devices genuinely absent from the reference library. This distinction may help inform how registries and researchers respond to unmapped records, as it suggests that at least some of these catalogue numbers merit targeted manual review and provider follow-up rather

than blanket exclusion from analysis. This finding may also contribute to informing more targeted data quality interventions and provider feedback to prevent future unmapped catalogue number submissions.

Taken together, these findings point to three primary opportunities to strengthen CJRR data quality going forward: adoption of an open-source implant reference library, implementation of the more active, real-time data quality processes used by other national registries, and adoption of a more complete, standardized minimum data set. The open-source reference library developed here offers CJRR-affiliated researchers a method of retrospectively validating and supplementing implant-level data without an IPL subscription and, as shown above, already exceeds the granularity of some CJRR-native fields. Until a comparable, publicly available resource exists, an open-source library of this kind remains a practical option for CJRR data validation and enrichment, particularly for researchers and institutions without IPL access.

Adopting the structured, real-time validation processes used by other registries would address several of the issues identified above at the point of entry rather than after the fact. Extending the barcode scanning already used in CJRR data entry [18,19] to auto-populate the manufacturer, component type, and JOINT_COMP fields directly from a linked reference library, consistent with the approach used by the Dutch Arthroplasty Register , could reduce reliance on manual selection. Moreover, automatically rejecting submissions with duplicate or mismatched barcode-to-component pairings before entry, as done in the AOANJRR [13,14], would prevent duplicate-component and manufacturer-misattribution errors before they enter the registry. A comparable structured, synoptic-reporting approach, used successfully at national scale in Canadian cancer surgery reporting [20], could extend this validation to the broader clinical and surgical fields (surgical approach, PCL status, cement use per component) that remain largely absent or ambiguous to derive from existing fields, consistent with the general finding that unclear data definitions are a leading cause of registry error [8]. Considering that clinician-entered data carries real workload costs, a phased pilot at high-volume centers, delegating non-clinical-judgment fields such as implant identifiers to trained data staff, would likely deliver much of this benefit while limiting disruption to surgical workflow.

Standardizing component-type naming and model-name formatting across submission pathways and the IPL, for example, reconciling "Knee-Femoral" and "Femoral Component," could be implemented with modest effort, even retrospectively, and comparable efforts elsewhere have improved cross-registry usability [21]. Cross-validating administrative fields, such as hospital teaching status, against independent, authoritative sources, such as specialty-specific residency accreditation records [22], would similarly improve classification reliability for fields shown here to disagree with more direct measures (Section B.2). More broadly, adopting minimum data set elements recommended by international bodies such as the International Society of Arthroplasty Registries would improve the CJRR's interoperability with other national registries and support the kind of cross-registry comparison already achieved by registries with more established data standards [10,11].

2.5.1 Limitations

While this open-source library contributed meaningful improvements, it is not without several limitations. The applicability matrix (Table B.3) simplified which fields apply to which component types. For example, mobility is currently recorded only for insert components, even though tibial baseplates could in principle also carry a mobility designation; extending the matrix to capture such cross-component compatibility fields would allow additional validation checks, such as flagging a fixed-bearing insert paired with a mobile-bearing-only baseplate, that the current pipeline cannot perform.

Moreover, the reference library's cleaned-catalogue-number and GTIN-substring recovery methods were heuristic. The multi-way GTIN substring matches suggest that some proportion of the recovered matches may be incorrect or ambiguous without manual verification. The recovery figures reported here should therefore be interpreted as an estimate of recoverable records rather than a validated correction.

Lastly, the reference library itself was incomplete. 25,253 unique catalogue numbers present in the library were not observed in the CJRR dataset used here. While 10,447 unique catalogue numbers submitted to the CJRR had no library match at all (may not have valid formatting for matching), and even among matched records, individual fields,

particularly dimensional attributes for less common component types, remained missing where no contributing source captured the relevant value.

2.5.2 Conclusion

Overall, these results support the hypothesis that a standardized, open-source implant library can identify and correct data errors in the CJRR, improving the reliability of implant-level registry analyses. These findings also clarify the limits of this approach: catalogue-number-based linkage remained vulnerable to non-unique identifiers and formatting inconsistencies on both the registry and reference library side, and any classification field, whether submitter-entered or library-derived, required cross-validation rather than being treated as ground truth.

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Chapter 3

Fixation

3.1 Abstract

3.1.1 Background

Cementless total knee arthroplasty (TKA) has gained traction internationally due to advances in implant design and fixation. However, evidence of its adoption in Canada remains limited. This study examined national trends in cementless TKA from 2019 to 2023 and assessed variation by patient sex, age, and province. Cementless trends were also compared to those reported by other national registries. Distributions of cemented and cementless implant models were also examined to contextualize the generalizability of adoption trends.

3.1.2 Methods

A retrospective cohort study was conducted using data from the Canadian Joint Replacement Registry (CJRR). Adults ($\geq$18 years) undergoing primary TKA between 2019 and 2023 were included. The primary outcome was fixation (cemented vs. cementless). Temporal trends were evaluated using Cochran-Armitage trend tests and linear regression; as-

sociations of fixation with sex, age, and province were assessed using Pearson's chi-squared tests of independence and multivariable logistic regression.

3.1.3 Results

A total of 218,229 primary TKAs were analyzed, of which 14.3% were cementless. The proportion of cementless TKAs more than doubled from 8.4% in 2019 to 18.6% in 2023 and was highly concentrated in a single implant system, with Stryker Triathlon Cementless accounting for over 90% of cementless TKAs nationally. Younger patients and men were more likely to receive cementless fixation, and fixation patterns among women resembled those of men roughly a decade older. Strong geographic variation was observed, with British Columbia and Alberta leading adoption and Manitoba and Saskatchewan showing the lowest uptake.

3.1.4 Conclusion

Cementless TKA use in Canada increased substantially from 2019 to 2023, though rather than broad cementless adoption, this is largely reflective of the uptake of a single implant system. This increase was particularly notable among younger patients and men, though significant provincial variation persists. These findings document a substantial acceleration in cementless implant use in Canada within the observed study periods.

Keywords: arthroplasty, knee, replacement, Canada, implant fixation, prosthesis fixation.

3.2 Introduction

Total Knee Arthroplasty (TKA) is a common, effective procedure for end-stage knee osteoarthritis, with rising procedure volumes driven by aging populations and broader indications [1,2]. Despite improvements in surgical technique and implant design [3], aseptic loosening and infection remain the leading causes of revision surgery [4].

One innovation to address these challenges is the use of cementless implant designs, in which implant fixation relies on bone ingrowth rather than on polymethyl methacrylate (PMMA) bone cement used for cemented fixation. While cementless designs have been around for decades, they never gained popularity over standard cemented models--perhaps because first-generation cementless models were associated with higher rates of early failure, with signs often pointing to poor fixation [5–7]. In contrast, cemented models offered immediate fixation and stability through synthetic bone cement, which fills the space between the implant and bone. Modern cementless designs, however, have benefited from advances in materials and design that promote osteointegration, enhancing long-term fixation while preserving bone stock [8,9]. Moreover, the literature suggests cementless models perform equally or better than cemented models [10–14], with particularly positive outcomes in obese populations compared to cemented implants [15–18], have the benefit of increased operating room efficiency [19,20], and reduced revision rates in younger and more active patients [17–19]. Despite this, cemented fixation remains the gold standard for TKA [24,25].

Nevertheless, cementless adoption has recently increased globally [9,26,27], particularly among younger patients and men [26,27]. Over the past decade, national registries from Britain, Australia, Sweden, and the United States have reported increased cementless TKA [27,28]. However, Canadian-specific data are limited, and little is known about how fixation method varies by sex, age, or region within Canada. Thus, this study aimed to (i) describe national trends in cementless TKA prevalence in Canada from 2019 through 2023 using Canadian Joint Replacement Registry (CJRR) data, (ii) compare Canadian trends with those of other national registries, (iii) within the CJRR data, evaluate variation by patient age, sex, province, and (iv) investigate implant model variation by fixation method as

a single dominant system could limit the generalizability of observed adoption trends to cementless TKA as a class.

Based on trends observed in other countries and the growing body of literature supporting the efficacy of cementless implants, we hypothesized that the use of cementless implants would have increased significantly over time. Moreover, men and younger patients were expected to be more likely to have received cementless implants. Significant provincial and model variation in cementless TKA was also expected due to the decentralized organization of the Canadian healthcare system [29] and the consequent distribution of procurement contracts, as well as previous reports [30].

3.3 Materials and Methods

3.3.1 Study Design

This analysis was a retrospective cohort study using de-identified, record-level data from the Canadian Joint Replacement Registry (CJRR) maintained by the Canadian Institute for Health Information (CIHI), covering fiscal years (May-April) 2019–2020 through 2023–2024. This study was carried out with IRB approval.

Data were accessed through CIHI's Graduate Student Data Access Program, through which revision data were not available. Parts of this material were based on data and information provided by the Canadian Institute for Health Information. However, the analyses, conclusions, opinions and statements expressed herein are those of the author and not necessarily those of the Canadian Institute for Health Information.

Publicly available fixation data from the CJRR annual reports for 2003-2011 were used to assess historical trends in cementless fixation. Fixation data for the years 2012-2018 were unavailable.

Similarly, fixation data from other national registry reports were used to compare national fixation trends worldwide from 2003-2024 (where data were available). Publicly available fixation data were extracted from reports from the CJRR (national, partially

mandatory) [31], Swedish Knee Arthroplasty Register (national, voluntary submission, complete coverage) [32–48], American Joint Replacement Registry (voluntary submission, does not collect coverage data) [49], Australian Orthopedic Association National Joint Replacement Registry (national, voluntary submission, complete coverage) [50], National (British) Joint Registry (national, mandatory submission, complete coverage) [51], and Dutch Arthroplasty Register (LROI, national, mandatory submission, complete coverage) [52].

3.3.2 Study Population in Canadian Joint Replacement Registry Data

The dataset included primary total knee arthroplasty procedures (with or without patellar resurfacing) for patients ≥18 years at the time of surgery. Cases with incomplete fixation data were excluded. The dataset was restricted to one record per procedure (identified via procedure ID); procedures with multiple distinct records were excluded to avoid ambiguity. Patient identifiers were unavailable, so multiple procedures for the same patient could not be identified. According to these data specifications, a total of 218,229 records were included (Section C.1).

3.3.3 Variables

The primary outcome was fixation method (cemented vs. cementless), defined by the intended fixation method of the tibial component based on the submitted CJRR catalogue number. Other variables investigated were fiscal year, implant model and manufacturer, patient age at surgery, patient sex (defined by CIHI as sex at birth [53]), and province/territory (restricted to those with mandatory CJRR submission or ≥70% coverage). The final provinces and territories included, and their average coverage, were Ontario (91.6%, mandatory reporting), British Columbia (94.3%, mandatory), Nova Scotia (94.1%, mandatory), Manitoba (99.5%, mandatory), Alberta (75.7%), Saskatchewan (96%), Newfoundland and Labrador (99.2%), and the Northwest Territories (97%). Implant model

was defined as the model name of the tibial component. Model variations such as differences in stability (i.e. cruciate retaining and posterior stabilized) were grouped together, and models comprising less than 5% of the cemented or cementless national total were not reported. The models reported included: Persona (Zimmer Biomet, Warsaw, IN, US), Triathlon (Stryker, Mahwah, NJ, US), NexGen (Zimmer Biomet, Warsaw, IN, US), and Attune (Depuy, Loughbeg Ringaskiddy, CK, IE) and are described in Table 3.4.

3.3.4 Data Analyses

All analyses were performed in R (v4.3.0) using the base R statistics package (unless otherwise specified) with a significance threshold of $\alpha = 0.05$. Descriptive statistics summarized fixation patterns by subgroup (patient sex, age, implant model, and province). Normality of patient age was confirmed via visual inspection (histogram, Q-Q plots). Temporal changes in cementless TKA usage were tested using Cochran-Armitage (proportions) trend tests. Publicly available historical CJRR data (2003-2011) were plotted alongside the study data (2019-2023) to assess long-term trends. Independent linear regressions were used to assess cementless temporal trends for the periods with observed data (2003-2011 and 2019-2023). Pearson's chi-squared tests of independence assessed sex–age and provincial variation; where the omnibus test was significant, post hoc pairwise comparisons of proportions were conducted with Bonferroni adjustment. Bonferroni adjustment was applied only to these pairwise comparisons; all other reported P-values (omnibus chi-squared tests, Cochran–Armitage trend tests and regression coefficients) are unadjusted. Effect sizes were reported as r for Cochran-Armitage trend tests ($r = Z/\sqrt{n}$; small: 0.10, medium: 0.30, large: 0.50) and as bias-corrected Cramér's V for chi-squared tests (small: 0.10, medium: 0.30, large: 0.50), using the rcompanion package [54,55].

To investigate factors contributing to cementless variation, a multivariable binary logistic regression model was fit to estimate adjusted odds ratios (OR) for cementless fixation. Covariates included fiscal year (centred at 2019), patient sex, age group (<50, 50-60, 60-70, 70-80, 80+), and province. Age and sex were included based on established associations with fixation preference [26,27]. Province was included based on exploratory analyses

showing variation in cementless rates across provinces, and other registries have reported regional variation in fixation use [33]. Province was specified using weighted effects coding (WEC), in which each provincial coefficient reflects deviation from the sample size-weighted national mean, avoiding reliance on an arbitrarily chosen reference province, given substantial interprovincial variation in CJRR sample sizes [56,57]. The OR and 95% CIs for the omitted province in this model were recovered via the weighted sum-to-zero constraint and the delta method [58,59]. Manitoba, Saskatchewan, and the Northwest Territories were excluded from this model due to sparse or absent cementless cases, precluding stable parameter estimation; descriptive fixation rates for these provinces are reported in Table 3.2. A conventional reference-coded model with Ontario as the reference province was also fit to aid interpretation. Model fit was assessed using McFadden's pseudo-R^2, which measures how much better the model predicts the outcome than a model with no predictors (0 = no improvement, 1 = perfect prediction; calculated as $(1 - \log L_{model} / \log L_{null})$) [77], and the area under the receiver operating characteristic curve (AUROC) [78]. Confidence intervals (to reflect uncertainty in the point estimates) for AUROC estimates were not computed; given the large sample sizes, sampling uncertainty in the AUROC estimates was expected to be small.

Temporal trends across national registries were examined using a descriptive comparative design.

3.4 Results

3.4.1 Participants

The study population comprised 218,229 primary TKA procedures in the CJRR, predominantly cemented, with cementless TKAs occurring primarily among younger patients and men (Table 3.1).

Table 3.1: Number of Primary Total Knee Arthroplasties (TKA) and demographic information by fixation for fiscal years 2019-2023.

Characteristic	**Cemented**	**Cementless**	***P*-value**
Mean Age, years (range)	68.9 (18-110)	66.4 (27-111)	<0.001
% Female	60.3	49.3	<0.001
Total TKA Count (%)	187,024 (85.7)	31,205 (14.3)	

3.4.2 Temporal Trends in TKA Fixation in Canada

Over the 5-year period (2019-2023), cementless TKA use increased significantly ($\chi^2_{\text{trend}} = 2590.1$, $P < 0.001$). In 2019, the percentage of total TKAs in Canada that were cementless was 8.4% and increased annually to 18.6% in 2023 (Fig. 3.1).

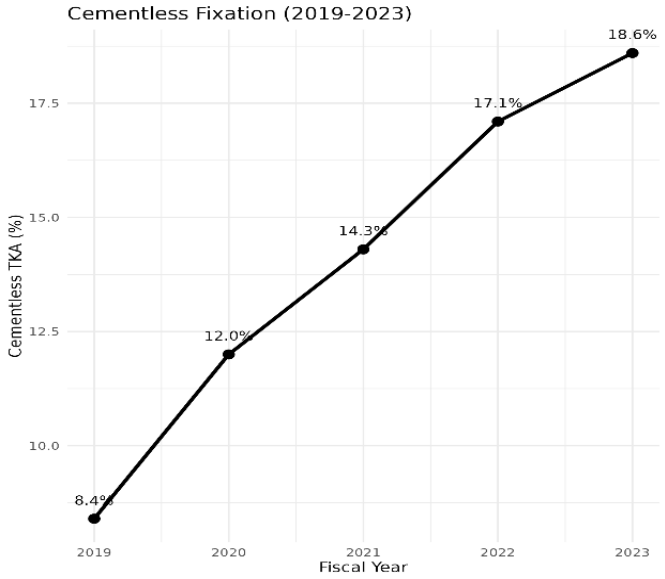


Figure 3.1: Percent cementless of total TKAs across fiscal years 2019-2023 in Canada.

Using publicly available data from the CJRR Annual Reports, cementless TKA adoption was examined from 2003 to 2023 (Fig. 3.2). National cementless rates were not

publicly reported from 2012-2018, and this period was excluded from all inferential analyses. Comparing the two periods with observed data, cementless adoption increased from ~3% (2003-2011) to 18.6% (2023). Linear regressions fit separately to the 2003-2011 and 2019-2023 segments indicated a slow rate of increase during 2003–2011 (0.3 percentage points/year, $R^2 = 0.55$, Adjusted $R^2 = 0.49$, $P = 0.022$) and a substantially faster rate during 2019–2023 (2.6 percentage points/year, $R^2 = 0.98$, Adjusted $R^2 = 0.98$, $P = 0.001$).

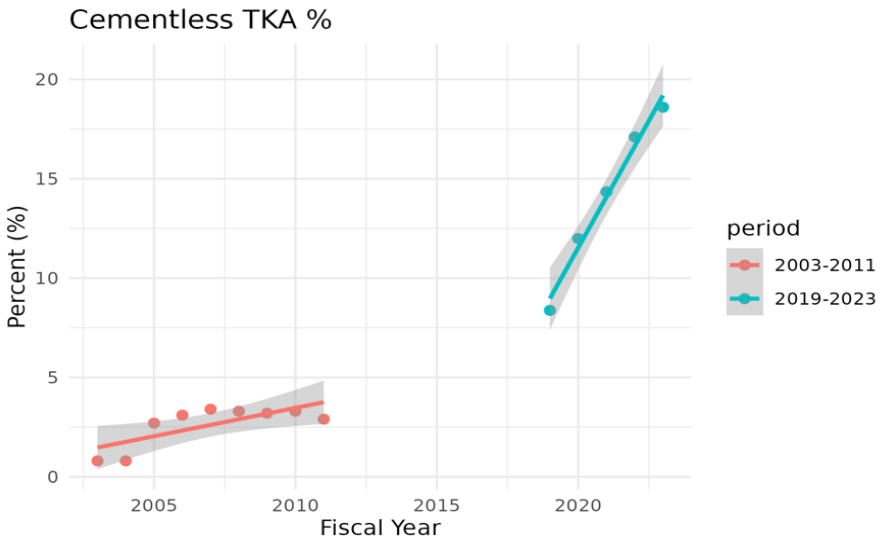


Figure 3.2: Percent cementless TKA for fiscal years 2003-2011 and 2019-2023.Using publicly available data from CJRR annual reports. Cementless fixation rates were not publicly reported for 2012-2018; this period was excluded from the figure. Separate linear regression lines with 95% confidence intervals are shown for each observed segment (2003-2011: $\beta = 0.29$ percentage points/year, adjusted $R^2 = 0.49$, $P = 0.022$; 2019–2023: $\beta = 2.56$ percentage points/year, adjusted $R^2 = 0.98$, $P = 0.001$).

3.4.3 Global Trends in Cementless TKA

Globally, the increased use of cementless implants observed in Canada is evident in other national registries (Fig. 3.3). Most comparable to Canada, the American Joint Replacement Registry shows low cementless adoption (<5%) from 2012 to 2017, followed by a sharp increase around 2017. However, the American registry reports even higher rates of

cementless adoption than Canada, reaching over 20% in 2023 [49]. The Australian Orthopedic Association National Joint Replacement Registry (AOANJRR) also shows increased cementless uptake from 2018 to 2023; however, unlike the Canadian and American reports, this occurs after a progressive decline in cementless use from 2003 (>25%) to 2018 (<10%) [50]. In contrast to the accelerated increase in cementless uptake observed in various registries over the past 5 years, the Swedish registry showed a slow, steady increase in cementless use, peaking at approximately 9% in 2021, followed by a decrease in the following 2 years [29–31]. Other registries, such as Britain's National Joint Registry (NJR) and the Dutch Arthroplasty Register (LROI), show relatively steady, low cementless adoption [51,52].

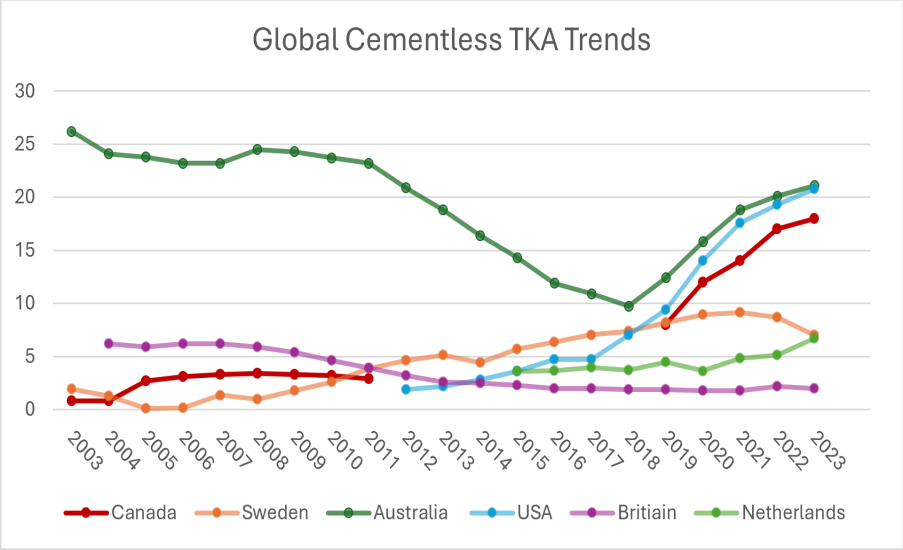


Figure 3.3: Cementless fixation trends from national joint registries (2003-2023, where data are publicly available). Joint registries included Canada (CJRR) [61], Sweden (Swedish Arthroplasty Register) [32–48], Australia (AOANJRR) [50], USA (AJRR) [49], Britain (NJR) [51], and the Netherlands (LROI) [52].

3.4.4 Sex, Age, & Provincial Variation in Canada

In the 2019-2023 CJRR data, sex-disaggregated analyses revealed similar trends: cementless adoption increased in both women ($\chi^2 = 1554.2$, $P < 0.001$, r = 0.11) and men ($\chi^2 = 1048.2$, $P < 0.001$, r = 0.11). However, men had higher rates of cementless TKA than women across all years (Fig. 3.4). Across age groups, the higher cementless rate among men was also apparent (Fig. 3.5). Age and sex significantly influenced cement use ($\chi^2 = 3401.6$, $P < 0.001$, V = 0.12); younger men had the highest cementless proportions, whereas older women had the lowest. Bonferroni-adjusted pairwise comparisons found that women had cementless TKA prevalence rates comparable to men approximately 10 years older (e.g., 60-70-year-old men vs. <50-year-old women: $P = 1.00$; Fig. 3.5, Table C.2).

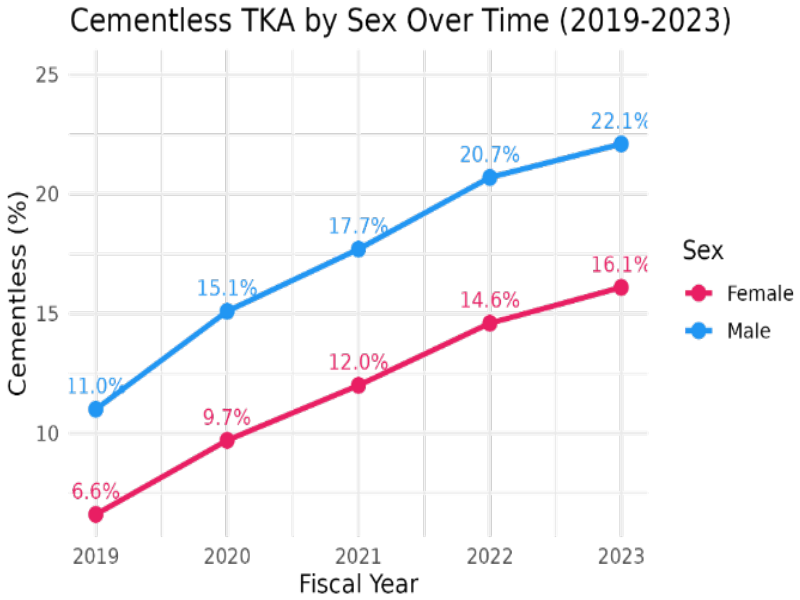


Figure 3.4: Percent cementless of total TKAs across fiscal years 2019-2023 in Canada by sex.

Cementless TKA prevalence varied substantially by province ($\chi^2 = 4481.5$, $P < 0.001$, V = 0.15; Table 3.2). Overall, from 2019 to 2023, British Columbia led in cementless use, with Alberta and Nova Scotia following closely, whereas Manitoba, Saskatchewan, and the

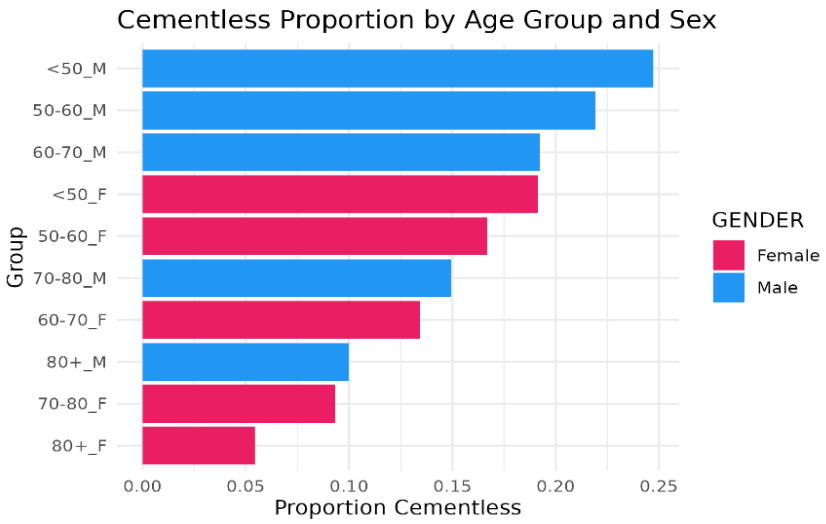


Figure 3.5: Proportion of cementless TKAs by sex and age group (2019-2023).

Northwest Territories had the lowest rates. Ontario, despite having the highest volume of TKAs in Canada, had substantially lower cementless TKA usage (13.5%) than the highest-use province, British Columbia (21.5%). Post hoc pairwise comparisons among provinces with recorded cementless procedures found that all province pairs differed significantly after Bonferroni adjustment (all adjusted $P < 0.01$).

Table 3.2: Total and mean percent cementless TKAs by province (2019-2023).

Province	**Total Percent Cementless**	**Mean Percent Cementless**
Alberta	19.8	19.6
British Columbia	21.5	21.8
Manitoba	0.12	0.08
Newfoundland & Labrador	6.0	5.2
Nova Scotia	18.1	17.8
Northwest Territories	0.0	0

Province	Total Percent Cementless	Mean Percent Cementless
Ontario	13.5	13.1
Saskatchewan	0	0
National (Overall)	14.3	14.1

To examine factors contributing to cementless fixation variability, a logistic regression model was fitted to estimate adjusted odds of cementless fixation, including fiscal year, sex, age group, and province (results in Table 3.3). Manitoba, Saskatchewan, and the Northwest Territories were excluded due to sparse or absent cementless cases (Table 3.2), which produced model separation. All covariates were statistically significant (all $P < 0.001$), though model fit was modest (McFadden's pseudo-$R^2 = 0.056$, AUROC = 0.671); the included factors had limited explanatory power for fixation choice. A conventional reference-coded model with Ontario as the reference province was also fit (Section C.2, Table C.1); the estimates for fiscal year, sex and age were consistent with the WEC model, confirming that results were not sensitive to the provincial coding scheme.

Consistent with descriptive trends, the odds of cementless use increased by 30% per year (OR = 1.30, 95% CI: 1.29-1.31, $P < 0.001$), corresponding to the increase from 8.4% to 18.6% over the study period. Men had 59% higher odds of cementless fixation than the weighted national mean (OR = 1.59, 95% CI: 1.55-1.63, $P < 0.001$). Unadjusted cementless rates increased from 11% to 22.1% in men versus 6.6% in 2019 to 16.1% in 2023 in women. The odds of cementless fixation decreased progressively with age compared to patients under 50, ranging from a 21% reduction in the 50-60-year-old group to a 77% reduction in patients over 80 years old (Table 3.3).

Significant geographic variation persisted after adjustment for year, sex, and age. Compared to the weighted national average rate of cementless fixation, the odds of cementless fixation were 56% higher in British Columbia (OR=1.56, 95% CI: 1.53-1.59, $P < 0.001$), 32% higher in Alberta (OR = 1.32, 95% CI: 1.28-1.36, $P < 0.001$), and 19% higher in Nova Scotia (OR = 1.19, 95% CI: 1.13-1.25, $P < 0.001$). Newfoundland and Labrador

had substantially lower odds than the national mean (OR = 0.30, 95% CI: 0.27-0.34, $P < 0.001$). Ontario, the largest contributor to the national sample (51% of included records), had adjusted odds below the national mean (OR = 0.82).

Table 3.3: Multivariable regression analysis for cementless fixation procedures (n = 218,229). OR = odds ratio, CI = confidence interval. Manitoba, Saskatchewan, and the Northwest Territories were excluded from the multivariable logistic regression model due to sparse or absent observed cementless cases, preventing stable parameter estimation. Descriptive fixation rates for these provinces are reported in Table 3.2. Model fit: McFadden's pseudo-R^2 = 0.056, AUROC = 0.671.

Predictor	**OR**	**95% CI**	**P-value**
Fiscal year (per year)	1.30	1.29-1.31	<0.001
Sex: Male vs. national mean	1.59	1.55-1.63	<0.001
Age <50 (reference)	-	-	-
Age 50-60	0.80	0.73-0.86	<0.001
Age 60-70	0.60	0.55-0.65	<0.001
Age 70-80	0.40	0.37-0.43	<0.001
Age 80+	0.23	0.21-0.25	<0.001
Alberta vs. national mean	1.32	1.28-1.36	<0.001
British Columbia vs. national mean	1.56	1.53-1.59	<0.001
Newfoundland & Labrador vs. national mean	0.30	0.27-0.34	<0.001
Nova Scotia vs. national mean	1.19	1.13-1.25	<0.001
Ontario vs. national mean	0.82	0.81-0.83	*

Predictor	OR	95% CI	P-value

*Ontario coefficient recovered via weighted sum-to-zero constraint; 95% CI was estimated using the delta method and reflects uncertainty propagated through the linear combination of directly estimated provincial coefficients; P-value not directly estimable.

3.4.5 Implant Model Trends

To assess whether cementless adoption in Canada reflected broad uptake across implant systems or concentration within specific models, implant model distribution was examined by fixation type. In contrast to the wider variety of implant models commonly used in cemented TKA (Table 3.4), cementless TKA predominantly used a single implant model: Stryker's Triathlon Cementless (Tritanium). Interestingly, while Zimmer/Biomet models comprised the majority of cemented models in Canada, their cementless models were not commonly used. In comparison, while Stryker accounted for a smaller share of the cemented market, it accounted for over 90% of the cementless implants in Canada.

Table 3.4: Top Implant models (tibial component) per fixation method. Models comprising less than 5% of the total cemented/cementless TKA volume are not listed. Cumulatively, these models account for 97.4% of procedures included in this study.

Fixation	Model (Manufacturer)	Percent
Cemented	Persona (Zimmer Biomet)	44.7
	Triathlon (Stryker)	26.2
	NexGen (Zimmer Biomet)	10.3
Cementless	Triathlon (Stryker)	90.8
	Attune (Depuy/J&J)	6.65

3.5 Discussion

This registry analysis of Canadian data from 2019 through 2023 demonstrated a national trend toward increased utilization of cementless TKA, aligning with international trends and supporting the hypothesis that adoption has increased over time. However, the cementless uptake was highly concentrated among a single implant system (Stryker Triathlon Cementless), suggesting that observed adoption patterns reflect the proliferation of one system rather than class-wide uptake of cementless TKA. Consistent with our other hypotheses, cementless fixation was more commonly used in men and younger patients, whereas cementless rates among women were comparable to those of men a decade older. These findings may suggest growing surgeon confidence in biologic fixation, particularly in younger populations perceived to have better bone quality and higher functional demands [5,9,21]. Geographic variation further demonstrated uneven use of cementless technology: provinces such as Alberta and British Columbia showed increased adoption, whereas Manitoba and Saskatchewan did not. Given the concentration of cementless adoption within a single implant system, the observed geographic variation may reflect the distribution of that system's procurement contracts and surgeon familiarity across regions as much as clinical selection. However, patient-level demographic factors and province together explained only a small proportion of variation in fixation choice (McFadden's pseudo-$R^2 = 0.056$, AUROC = 0.671), suggesting that the decision is substantially driven by factors operating above the patient level.

The rise in cementless fixation observed in this study also reflects a broader historical trend. The observed Canadian trend is consistent with international registry data, particularly from the American and Australian registries, which also report recent accelerated cementless adoption. Because no Canadian data are available for 2012–2018, we cannot determine when the observed acceleration began. However, if consistent with the American and Australian patterns, it would suggest the shift likely began around 2017–2019 [26,27].

Review of the CJRR's annual reports of revision rates for primary TKA by fixation shows improved performance of cementless models [2,56,62]. The 2024-2025 CJRR report is the first to demonstrate significantly lower revision risk for cementless versus cemented

TKA (age/sex-adjusted HR = 0.87, 95% CI 0.79-0.95, $P < 0.001$) and lower unadjusted cumulative percent revision rates at 13-year follow-up; a finding not significant in earlier reports with shorter follow-up [2,56,62]. The 2024-2025 CJRR report also noted that 83% of cementless implants were from a single (unspecified) manufacturer, but prior to this report, only fixation type has been reported for TKA, with no implant model or manufacturer information provided [56].

The strong negative association between cementless TKA and age may support the idea that cementless implants are selectively used in younger patients, anticipating improved fixation and more prolonged implant survival [28]. Moreover, because younger patients have a longer remaining life expectancy and may therefore face a greater lifetime likelihood of revision, the bone-sparing nature of cementless TKA may offer an advantage for subsequent revision by preserving bone stock and avoiding the additional bone removal that may be required to remove cement from the bone surface [28]. The finding that women are treated similarly to men approximately a decade older further underscores how biological considerations, such as bone quality, influence surgical decision-making, as postmenopausal women often exhibit accelerated bone mineral density loss [63,64]. However, the evidence base supporting this pattern is not definitive. While some studies have suggested that, while controlling for age and sex, cementless TKA performs equally or better than cemented [9,27,28,30,65,66], others have reported higher revision rates and component migration in cementless TKA [64,67]. Notably, there is no published evidence definitively demonstrating inferior cementless TKA outcomes in older women, nor superior cementless outcomes in younger men, compared to cemented alternatives when controlling for patient selection. Documenting these demographic patterns at the time of surgery is therefore important: if current selection practices are not based on outcomes evidence, they should be accounted for as potential confounders in future comparative effectiveness analyses of fixation method. Outcomes data linking registry-level fixation patterns to long-term revision rates, stratified by age and sex, are needed to determine whether current selection practices optimize patient benefit.

Regional effects were also observed across provinces, reflecting how differences in provincial health care systems and procurement policies may shape fixation practices. Alberta

and British Columbia had high adoption of cementless TKA, whereas Manitoba and Saskatchewan had minimal usage. However, Alberta had significantly lower reporting coverage (75.7%) than the other included provinces, which had >90% coverage. Therefore, estimates of Alberta's cementless uptake may be inaccurate. Even Ontario, which accounted for over 50% of all TKA procedures in Canada, showed relatively low cementless uptake. This provincial variation may be driven by independent provincial healthcare systems, in which each province manages its own healthcare expenditures and implant procurement is decentralized at the hospital level [68]. Thus, factors beyond patient need, such as surgeon training and familiarity [69], hospital group purchasing contracts, and the competitive bidding process, may substantially influence implant procurement and clinical practice [40–42]. The modest fit of the multivariable logistic regression model (McFadden's pseudo-R^2 = 0.056), despite all covariates reaching statistical significance (as expected, given the large sample size), indicated that patient-level demographic and provincial factors explained less than 6% of the variation in fixation choice, suggesting that unmeasured factors, such as surgeon- and institution-level variables, likely account for much of the remaining variability. The limited diversity of implant models used nationally (Table 3.4), particularly for cementless TKAs, further illustrates how institutional factors such as procurement may influence fixation, with a single model (Stryker Triathlon) used in more than 90% of cementless procedures.

The low prevalence of robotic-assisted knee surgery in Canada during this study period (0.09% in 2019 to 3.3% in 2023 [56]) and the use of cemented fixation in over 75% of robotic-assisted procedures during the study period [56], suggests that the observed concentration of cementless Stryker Triathlon reflects implant procurement decisions rather than robotic platform bundling. This contrasts with markets such as the United States, where greater robotic adoption (16.3% of TKAs in 2023) has coincided with increased cementless uptake [49]. However, given the low adoption of robotic-assisted surgery in Canada and the predominance of cemented fixation among robotic-assisted procedures, the increase in cementless fixation observed in Canada cannot be fully attributed to increased adoption of robotic-assisted surgery.

It is also possible that the cementless Stryker Triathlon dominance reflects perceived

clinical success of the cementless system or decreasing relative costs of cementless implants over time [20]. However, registry reports of the cementless Stryker Triathlon show variable performance across registries. The American Joint Replacement Registry reported that the 10-year unadjusted revision rate among patients aged >65 ranged from 2.22% to 2.87%, depending on the stability design [49]; these rates were higher than those reported for other cementless systems. In contrast, the Australian Orthopedic Association National Joint Replacement Registry reported relatively lower 10-year cumulative revision rates for cementless Stryker Triathlon implants (4.0-5.2%) compared to their other reported cementless systems [50]. Such concentration, despite mixed performance reports, suggests that factors aside from purely clinical considerations may shape implant selection and, consequently, fixation method.

The literature has reported improved outcomes for cementless TKA in obese populations [17,18] as well as in younger and more active patients [72–74]. Changes in patient demographics or in patient selection for cementless TKA based on these factors could perhaps contribute to the accelerated uptake of cementless TKA in Canada. However, this dataset did not include patient body mass index (BMI) information and therefore could not be directly analyzed. Statistics Canada has collected BMI information for 2019-2022 and has not reported any notable increase in obesity among relevant patient age groups in the TKA population (35-65+ years) [75]. Moreover, although data on patient activity levels were not available, the mean age of patients in the cementless and cemented TKA populations differed by less than 3 years (68.9 years cemented vs 66.4 years cementless). This suggests that patient age may play a role in selecting cementless fixation, but the relatively small difference in mean age suggests that other patient- and surgeon-related factors likely also contribute to fixation choice.

While this study benefited from access to a large, national dataset with detailed stratification by patient, province, and implant characteristics, limitations persist. This dataset only captured 5 years of record-level data and did not include all provinces. Moreover, the historical trend analysis had a 6-year data gap from 2012-2018, limiting our ability to identify the inflection point in increased cementless adoption and hindering comparisons with other registries during that period. Additionally, fixation was determined solely by

the tibial component design, not surgeon-confirmed technique, thereby limiting the granularity of data on potential hybrid-fixation TKAs or off-label use. Moreover, the analysis lacked direct clinical outcomes, such as revision rates, and surgeon-level data, which likely contribute to the variation reported [69]. Patient identifiers were also unavailable for this study; thus, bilateral surgeries could not be identified. This violated the independence assumption of the inferential analyses, potentially leading to slightly underestimated standard errors and narrower confidence intervals. However, this was not expected to meaningfully alter the study conclusions, as bilateral cases were expected to be rare; a 2016 report from the CJRR documented rates of 2% and 9% for simultaneous and staged (within 1 year) bilateral TKAs, respectively [76]. As more than 90% of cementless TKAs in this study utilized a single implant system, findings on demographic and geographic adoption patterns may not generalize to cementless TKA systems more broadly.

Future work should integrate clinical outcomes, particularly revision and survival rates, to assess whether the observed trends translate into improved long-term results. Based on the significant difference in use by sex, sex-disaggregated survival analyses should be considered. Linking registry data to surgeon-level variables could also help clarify how surgical decision-making interacts with institutional and regional norms (i.e. perceived implant success, cemented versus cementless implant pricing). Finally, further investigation into procurement policies may reveal how industry dynamics shape surgical practice patterns.

3.5.1 Conclusion

Cementless TKA use in Canada has increased substantially, most commonly among younger patients and men, though adoption remains uneven across provinces. We noted provincial disparities and a single model accounting for most cementless implants. Future studies incorporating revision and functional outcomes are needed to determine whether increased cementless fixation translates into improved patient outcomes and to inform equitable, evidence-based fixation strategies.

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Chapter 4

Patellar Resurfacing

4.1 Abstract

4.1.1 Background

In total knee arthroplasty (TKA), patellar resurfacing remains controversial, with no definitive evidence in the literature supporting or refuting the practice. Similarly, TKA stability (constraint) decisions also lack clear evidence to guide optimal surgical decision-making. Insert stability choices have also diversified beyond the traditional cruciate-retaining (CR) versus posterior-stabilized (PS) dichotomy, with medial-pivot (MP) and anterior-stabilized (AS) designs now widely used. To describe current patellar resurfacing and tibial insert stability design trends in Canadian TKA practice and investigate potential influences on these surgical decisions, this study characterized national and provincial rates of patellar resurfacing and tibial insert stability design (CR, PS, MP, AS) and examined predictors of each.

4.1.2 Methods

A total of 222,173 primary TKA records from the Canadian Joint Replacement Registry (2019-2023) were analyzed. Stability design was classified into four categories (PS, CR, MP, AS); medially congruent and medial-pivot inserts were grouped as MP. Temporal and provincial variation were assessed using Pearson's chi-squared tests of independence, Cochran-Armitage trend, and Bonferroni-adjusted pairwise comparisons. Binary logistic regression (patellar resurfacing) and multinomial logistic regression (stability design, CR reference) were used to evaluate age, sex, fiscal year, and province (weighted effects coding) as predictors, adjusting for the others.

4.1.3 Results

Over the study period, 43.6% of TKAs included patellar resurfacing. PS was the most common design (42.9%), followed by MP (22.0%), CR (20.7%), and AS (14.5%). Among TKAs with patellar resurfacing, PS designs were substantially more common than CR, MP, or AS. Utilization of MP and AS designs increased significantly over the study period (OR per fiscal year 1.447 and 1.212, respectively, vs. CR), while PS use declined modestly (OR 0.962). Provincial variation was substantial for both stability design and patellar resurfacing (all $p<0.001$), with Manitoba showing markedly higher PS and patellar resurfacing use and Newfoundland & Labrador showing the lowest. Patellar resurfacing and stability design were independently associated (Cramér's $V=0.195$), but each showed distinct predictor profiles; sex and age effects were small in magnitude despite statistical significance.

4.1.4 Conclusion

TKA stability design selection in Canada has shifted meaningfully toward MP and AS designs over 2019-2023, with pronounced provincial variation in both stability design and patellar resurfacing practice, suggesting these decisions are shaped substantially by regional practice patterns rather than patient-level factors alone.

Key words: knee arthroplasty, patellar resurfacing, cruciate retaining, posterior stabilized, medial pivot

4.2 Introduction

The steady increase in total knee arthroplasty (TKA) demand globally necessitates the need for increased evaluation and improvement of knee implant design and utilization [1]. One highly controversial topic in implant design and its impact on clinical outcomes is patellar resurfacing, in which the underside of the patella is replaced with a prosthesis component. The decision to perform patellar resurfacing in TKA is often at the discretion of the surgeon, and usually based on the surgeon's personal preference and experience with particular implant designs [2–4].

Alongside the debate over patellar resurfacing is often the topic of stability. The primary TKA stability options are posterior cruciate ligament (PCL)-retaining (cruciate-retaining [CR]) and PCL-sacrificing, posterior-stabilized (PS) designs. CR designs are generally flatter and less conformed to the femoral condyles, relying on the preserved PCL for anterior-posterior stability and femoral rollback during knee flexion. In contrast, PCL-resecting (PS) designs generally include a cam-post mechanism, in which femoral cams articulate with a tibial post to control femoral rollback [5]. Two additional design philosophies with optional PCL-resection are increasingly reported: medial pivot (MP) designs, which achieve stability through a highly conforming, ball-in-socket medial compartment paired with a less constrained lateral compartment to replicate native knee kinematics, and anterior-stabilized (AS) (or ultra congruent) designs, which rely on insert geometry (typically a raised anterior lip) rather than a cam-post mechanism to prevent anterior tibial translation [5]. Unlike PS, which is widely reported across international registries as a discrete category, MP and AS designs are less consistently distinguished and are often collapsed into broader "Minimally Stabilized" categories, obscuring potential differences

in utilization and outcomes between these mechanistically distinct designs. In the CJRR specifically, CR, MP, and AS inserts are grouped together as "Minimally Stabilized (CR)", which thus may overestimate the actual number of cruciate retaining procedures, as MP and AS inserts are indicated for use with or without PCL resection. However, many other registries, including the Australian, Dutch, and American registries, report at least CR and MP separately [8–8]. Again, the decision to use a CR, PS, MP, or AS component is at the discretion of the surgeon, who may consider their own preference, experience, or anatomical factors such as condition of the PCL or intraoperative gap measurements in their decision [3,9,,10].

Many studies have conflicting conclusions regarding the clinical efficacy of patellar resurfacing [11]. Numerous studies have reported no significant differences in functional outcomes between TKA procedures with and without patellar resurfacing, suggesting that it may add unnecessary time, cost, and risk of complications without providing significant benefit [12,13]. However, other studies have suggested that not resurfacing the patella may lead to greater anterior knee pain [14–16] and increased pain-related revision rates [17,18], even if there were no significant functional differences.

Similarly, the literature is equally murky on the topic of TKA stabilization, though most comparative evidence to date has focused narrowly on CR versus PS. While some studies showed no significant differences in patient outcomes between PS and CR procedures [19], others have reported PS to be superior in measures such as range of motion, and CR to be superior in terms of long-term survivorship [20,21]. Moreover, PS designs are also associated with increased wear, patellar clunk/crepitus, and post-fracture complications [21–23]. Hence, the PS versus CR debate remains ongoing. In regards to patellar resurfacing, it seems the stabilization method has a significant impact, as outcomes often differ between stabilization methods with and without patellar resurfacing [24].

National registries also provide an overview of patellar resurfacing utilization and long-term outcomes. The Canadian Joint Replacement Registry's (CJRR) latest report (2024-2025) reports that of all primary knee replacements in 2024-2025, 33.0% included patellar resurfacing and 57.5% did not [25]. This is a notable shift from their immediately preceding report (2021-2022), which reported that 45.2% of procedures had patellar resurfacing and

44.7% did not [26]. In the 2024-2025 report, they also report that TKA without patellar resurfacing showed a slightly higher cumulative percent revision (CPR) at 10-year follow-up than those with resurfacing (age- and sex-adjusted hazard ratio (HR) = 1.14; 95% confidence interval (CI): 1.10-1.18; p<0.001) [25]. Moreover, considering implant stability, in addition to patella resurfacing, posterior stabilization without patellar resurfacing had the highest CPR over the 13-year period, whereas CR with resurfacing had the lowest [21]. CR non-resurfaced procedures had a significantly higher age- and sex-adjusted hazard ratio after 1-year of follow-up compared to the CR resurfaced implants (HR = 1.12; 95% CI: 1.01-1.21; p = 0.002). Similarly, PS non-resurfaced implants had a higher adjusted hazard ratio than PS resurfaced implants (HR = 1.19; 95% CI: 1.12-1.26; p<0.001). When comparing CR and PS implants both with and without patellar resurfacing, the CR implants had a significantly lower hazard ratio (Resurfaced: HR = 0.77; 95% CI: 0.72-0.82; p<0.001, Non-resurfaced: HR = 0.084; 95% CI: 0.79-0.90; p<0.001). These findings, specifically that patellar resurfacing and CR implants had the lowest revision rates, suggest substantial interplay between implant stability and patellar resurfacing on TKA revision. Notably, CJRR reporting at the national summary level, without disaggregating MP and AS designs from broader stability categories, may limit insight into how these specific design philosophies relate to patellar resurfacing decisions and outcomes.

International trends in patellar resurfacing and stabilization also vary. In America, patellar resurfacing dominated TKA, with 85.6% of TKAs including patellar resurfacing in 2024, and no significant difference in CPR at 10-year follow-up [8]. The American Joint Replacement Registry also reported higher CPR among PS designs than among all other stabilization methods, with CR designs having the lowest CPR [8]. MP designs had CPR similar to that of PS designs, while AS inserts had lower revision rates, more similar to the CR inserts [4]. Despite this, PS utilization remains more common than CR in the United States (34.1% vs 6.6% in 2024), though medial congruent showed substantially increased uptake (42.9% in 2024) [8]. AS and MP remain conservatively used, with 5.6% and 3.9% utilization, respectively, in 2024 [8]. Similarly high patellar resurfacing rates were reported in the Netherlands, with stable rates from 2015-2024 averaging about 80% [7], and Australia, with 81.2% in 2024 [6]. The Netherlands also reported consistent stabilization

trends, with 60% PS, 36% CR, and 1.5% MP utilization from 2015 to 2024 [7]. Similar to the CJRR, the Australian registry also reported lower CPR with patellar resurfacing from 6 months onwards, and for all stability types, those with patellar resurfacing had lower revision rates [6]. They also reported that PS designs had higher revision rates than CR designs, supporting the preference for CR designs (77.4% of primary procedures were CR in 2024, 12.4% PS, and 10.2% MP) [6]. For MP designs, when the patella was resurfaced, there was no difference in revision rates compared to CR, but without resurfacing, MP designs had a higher revision rate than CR [6]. One outlier in patella utilization is Sweden, which reported only 3% patella use in 2023, and no significant difference in revision risk for the most recent period (2014-2023) [27]. Sweden also showed a strong preference for CR designs, with only 3.9% use of PS design in primary TKAs in 2023 [23]. Sweden does not report MP-specific utilization or revision rates. Overall, patellar resurfacing rates vary by country, with no international consensus on preferred practice, although most registries reported lower revision rates with patellar resurfacing. However, regarding stability design, there is stronger consensus among these registry reports in terms of revision rates favouring CR designs over others.

This study aimed to investigate Canadian trends in patellar resurfacing and stability designs. As both the decision to resurface the patella and to resect the PCL are surgeon-dependent, this analysis provided more granular insight into national surgical practices. Unlike prior registry reports that collapse stability into a binary CR/PS framework, this study leveraged the CJRR's implant-level coding to classify stability design into four categories: cruciate-retaining (CR), posterior-stabilized (PS), medial pivot (MP), and anterior-stabilized (AS), providing previously unreported information on the provincial and temporal variation in patellar component use and stability design, and investigating potential differences among patient populations by age and sex.

4.3 Methods

4.3.1 Study Design

Canadian Joint Replacement Registry (CJRR) data from 2019 to 2023 were used in this retrospective cohort study. The Canadian Institute for Health Information's (CIHI) Graduate Student Data Access Program was used to access this data. Revision data, and hospital nor surgeon identifiers were available through this program.

Parts of this material are based on data and information provided by the Canadian Institute for Health Information. However, the analyses, conclusions, opinions and statements expressed herein are those of the author and not necessarily those of the Canadian Institute for Health Information.

4.3.2 Study Population

Total knee arthroplasty procedures (with or without patellar resurfacing), with a minimum patient age of 18 years, were included in this study. To ensure sufficient coverage, only reporting provinces with mandatory CJRR submission or minimum 70% submission rates were included. Such provinces and territories with acceptable coverage rates included Ontario (91.6%, mandatory reporting), British Columbia (94.3%, mandatory), Nova Scotia (94.1%, mandatory), Manitoba (99.5%, mandatory), Alberta (75.7%), Saskatchewan (96%), Newfoundland and Labrador (99.2%), and the Northwest Territories (97%). However, the Northwest Territories was excluded from these analyses due to small sample size (<150 procedures from 2019-2023), which when disaggregated by stability design and patellar resurfacing resulted in sparse cell counts, hindering analysis. Records with missing implant stability information were excluded from analysis (Appendix, Fig. D.1).

4.3.3 Variables

Presence of a patellar component in the patient record was the primary variable of interest. The stabilization design of the tibial insert was also considered and classified into four categories based on implant catalogue numbers and manufacturer-specified stability design collected and organized in the open-source implant reference library (Chapter 2). Inserts classified by the manufacturer as posterior stabilized or fully stabilized were categorized as posterior-stabilized (PS). Inserts classified specifically as "CR" or "Cruciate Retaining" were categorized as cruciate retaining (CR). Inserts classified as medially congruent or medial pivot were categorized as medial pivot (MP). True medial-pivot designs use a single-radius femoral component paired with a concave, ball-and-socket medial tibial surface, whereas medially congruent designs use a multi-radius (J-curve) femoral geometry with a more posterior dwell point and lower medial constraint [28]. Both share the aim of replicating native medial-pivot kinematics but differ slightly in geometry and degree of constraint. Some registries (e.g., AJRR) report them separately, so MP as defined here should be interpreted as an aggregate medial-stabilized family rather than a pure medial pivot group. Inserts classified as anteriorly or condylar stabilized were categorized as anterior-stabilized (AS). Inserts classified as hinge or rotating hinge components were excluded from the analysis. Monoblock tibial components, in which the tibial baseplate and polyethylene bearing form a single non-modular piece, were retained in the primary analysis because manufacturer catalogue data permitted stability-design classification for these components; a parallel sensitivity analysis excluding monoblock components produced materially unchanged results (Section D.1) and is summarized alongside the primary findings.

Subgroup analyses were also conducted according to reporting province, fiscal year (May-April, 2019-2023), and patient demographics (age, sex (defined by CIHI as sex at birth [29])). Trends by implant model system were also investigated. The models reported included: Persona, NexGen, and Vanguard from Zimmer Biomet (Warsaw, IN, US); Triathlon from Stryker (Mahwah, NJ, US); Legion and Genesis from Smith & Nephew (London, United Kingdom); Evolution and Advance from MicroPort (Shanghai, China); and Attune and LCS from DePuy Synthes (Loughbeg Ringaskiddy, CK, IE).

4.3.4 Statistical Analyses

The distribution of patellar resurfacing and implant stability design over time was assessed using the Cochran-Armitage test for trend in proportions. Temporal trends were assessed individually for patellar resurfacing and for each of the four stability categories (CR, PS, MP, AS), as well as for each of the eight patellar resurfacing and stability design combinations. The overall national distribution of patellar resurfacing and stability design combinations was described using counts and proportions. Effect sizes for trend tests were reported as the correlation coefficient r (with r^2 also presented for interpretability) and classified using Cohen's (1988) conventional thresholds for r: negligible ($r < 0.10$), small ($0.10 \leq r < 0.30$), moderate ($0.30 \leq r < 0.50$), and large ($r \geq 0.50$) [26].

Subgroup analyses examined variation in patellar resurfacing rates, implant stability, and their combination by province, patient sex, and age group using Pearson's chi-squared tests of independence. Where the omnibus test was significant, pairwise post hoc provincial comparisons for patellar resurfacing were conducted with Bonferroni correction (adjusted $\alpha = 0.00238$). Bonferroni correction was applied only to these pairwise comparisons; all other reported p-values are unadjusted. Effect sizes for all chi-squared tests were reported as Cramér's V, calculated as

$$V = \sqrt{\frac{\chi^2}{(N \times (\min(r, c) - 1)}}$$

where r and c are the numbers of rows and columns of the contingency table, and interpreted using thresholds adapted from Cohen (1988) [30] adjusted for table dimension by dividing the conventional thresholds for a 2 × k table (negligible $V < 0.10$, small $0.10 \leq V < 0.30$, medium $0.30 \leq V < 0.50$, large $V \geq 0.50$) by $\sqrt{(\min(r, c) - 1)}$ [50].

Two multivariable logistic regression models were constructed to identify independent predictors of each surgical decision. Patellar resurfacing and stability construct were modelled as separate outcomes, as both represent surgical decisions made at the time of the procedure without a definable causal ordering. Their co-occurrence is reported descriptively. Including one as a covariate in the model of the other may introduce simultaneity

bias, as both decisions are likely influenced by shared factors such as surgeon preference and implant system availability. The first model examined predictors of stability design, with age at surgery, sex, province, and fiscal year as covariates. Province was specified using weighted effects coding (WEC), in which each provincial coefficient reflects deviation from the sample size-weighted national mean rather than from an arbitrarily chosen reference province [50]. The second model examined predictors of patellar resurfacing, with age at surgery, sex, fiscal year, and province as covariates. Variance inflation factors (VIFs) were calculated for all predictors in both regression models to assess collinearity using the car package in R [31]; generalized VIFs (GVIFs) were calculated for categorical predictors with more than two levels. All VIF and GVIF values were below 1.06, indicating that collinearity was not a meaningful concern. Odds ratios (OR) and 95% confidence intervals (CI) were reported for all logistic regression models. Model fit was assessed using McFadden's pseudo-R^2 which compares the log-likelihood of the fitted model with that of an intercept-only model ($1 - \log(L_{model}) / \log(L_{null})$) [48], and the area under the receiver operating characteristic curve (AUROC) [49]; for the multinomial stability-design model, a multiclass AUROC was calculated using the Hand and Till generalization, which averages the pairwise AUROCs across all pairs of outcome categories (0.5 = chance-level discrimination; 1 = perfect discrimination) [51]. Confidence intervals for AUROC estimates were not computed, although these can be readily obtained to reflect uncertainty in the point estimates. Given the large sample sizes, AUROC estimate sampling uncertainty was expected to be small. Conventional reference-coded models with Ontario as the reference province were also fit to aid interpretation (Section D.3).

The 5 most common implant systems within each patellar resurfacing and stability design combination were identified by grouping by model names and frequency. Implant models with fewer than 100 procedures were excluded from this analysis.

All analyses were performed using R (v4.3.0).

4.4 Results

4.4.1 Participants

The final study population included 222,173 TKA procedures. Overall, most procedures were performed on female patients and did not include patellar resurfacing; posterior-stabilized was the single most common stability design nationally, followed by medial-pivot, cruciate-retaining, and anterior-stabilized designs (Table 4.1). Typically, in the CJRR (and other registries), MP and AS designs are frequently collapsed into a broader minimally stabilized or cruciate-retaining category; disaggregating these categories showed that true CR utilization in Canada is considerably lower than a binary CR/PS framework would have suggested. Provincially, the volume of TKAs was quite skewed. Ontario had the highest number of TKAs (51% of the national total), whereas provinces such as Nova Scotia and Newfoundland and Labrador accounted for less than 5% of the national total (Table 4.2).

Table 4.1: Cohort description. TKA = total knee arthroplasty, CR = cruciate-retaining; PS = posterior-stabilized; MP = medial-pivot; AS = anterior-stabilized.

Total TKA (n)	**Mean Age (SD)**	**Female (%)**	**Patellar Resurfacing (%)**	**Posterior Stabilized (%)**	**Cruciate Retaining (%)**	**Anterior Stabilized (%)**	**Medial Pivot (%)**
223,173	68.5 (8.7)	58.6	43.6	42.9	20.7	14.5	22.0

Table 4.2: Provincial distribution of TKA volume and patellar resurfacing and stability design utilization rates. Northwest Territories not reported due to small volumes and risk of patient identification.

Province	TKA (n)	Percent Patellar Resurfacing	Percent PS	Percent CR	Percent MP	Percent AS
Manitoba	11,927	63.3	84.1	8.1	X	X
Saskatchewan	12,759	50.8	18.2	20.1	X	X
British Columbia	44,920	46.0	33.4	15.9	29.7	21.0
Nova Scotia	9,420	43.4	51.5	29.9	1.0	17.7
Ontario	113,580	41.8	41.1	23.2	20.0	15.6
Alberta	24,643	41.3	59.5	15.4	14.2	10.9
Newfoundland & Labrador	4,924	19.0	34.8	44.9	8.5	11.8

Abbreviations: TKA = total knee arthroplasty; PS = posterior stabilized; AS = anterior stabilized; CR = cruciate retaining; MP = medial pivot. X = suppressed in accordance with CIHI disclosure guidelines because cell counts fewer than 5 cannot be reported. Additional cells may be suppressed to prevent residual disclosure.

4.4.2 Distribution of Patellar Resurfacing and Stability Design Combinations

Of the national total, 23.4% of TKAs were PS with patellar resurfacing, 19.5% were PS without patellar resurfacing, 13.6% were MP without patellar resurfacing, 12.9% were CR without patellar resurfacing, 10.2% were AS without patellar resurfacing, 8.4% were MP with patellar resurfacing, 7.8% were CR with patellar resurfacing, and 4.3% were AS with

patellar resurfacing (Fig. 4.1). The overall distribution of the eight patellar resurfacing-stability design combinations differed significantly from what would be expected under independence ($\chi^2 = 8404.6$, df = 3, $p < 0.001$, Cramér's V = 0.195, small effect), indicating a modest association between the two surgical decisions. PS was the single most common stability design regardless of patellar resurfacing status, but the composition of the remaining three designs differed by resurfacing status. When the patella was resurfaced, MP was the second most common design (19.1% of resurfaced procedures), CR had similar use (17.8%), but AS rates were much lower (9.8%). However, when the patella was not resurfaced, MP (24.2%), CR (22.9%), and AS (18.2%) were comparatively evenly matched. This pattern differs from a binary CR/PS framework, under which MP and AS utilization would be attributed entirely to a combined "CR" category, inflating apparent CR use, and reducing the substantial difference between PS and other stability design use in patellar resurfacing procedures, it would also show predominantly "CR" use in procedures without patellar resurfacing (Fig. 4.1; see Section D.1 for an alterative "Minimally Stabilized" plot with CR, MP, and AS grouped).

4.4.3 Temporal Trends in Patellar Resurfacing and Implant Stability

Between 2019 and 2023, the rates of patellar resurfacing in TKA decreased significantly ($\chi^2 = 1602.4$, $p < 0.001$, r = 0.085, $r^2 = 0.007$) from 48.8% in 2019 to 38.0% in 2023 (Fig. 4.2), an absolute decrease of 10.9 percentage points over the study period. Each of the four stability design categories also showed a statistically significant temporal trend (all $p < 0.001$; Fig. 4.3), but the direction and magnitude of these trends diverged substantially once disaggregated. PS utilization decreased from 53.4% in 2019 to 33.1% in 2023, an absolute decline of 20.3 percentage points ($\chi^2 = 5335.3$, r = 0.155, $r^2 = 0.024$). MP utilization more than tripled, from 10.6% in 2019 to 32.3% in 2023 (an absolute increase of 21.8 percentage points), representing both the largest absolute shift and the strongest trend of any stability design ($\chi^2 = 9030.6$, r = 0.202, $r^2 = 0.041$). AS utilization increased more modestly, from 12.0% to 16.9% ($\chi^2 = 540.9$, r = 0.049, $r^2 = 0.002$). In contrast to the

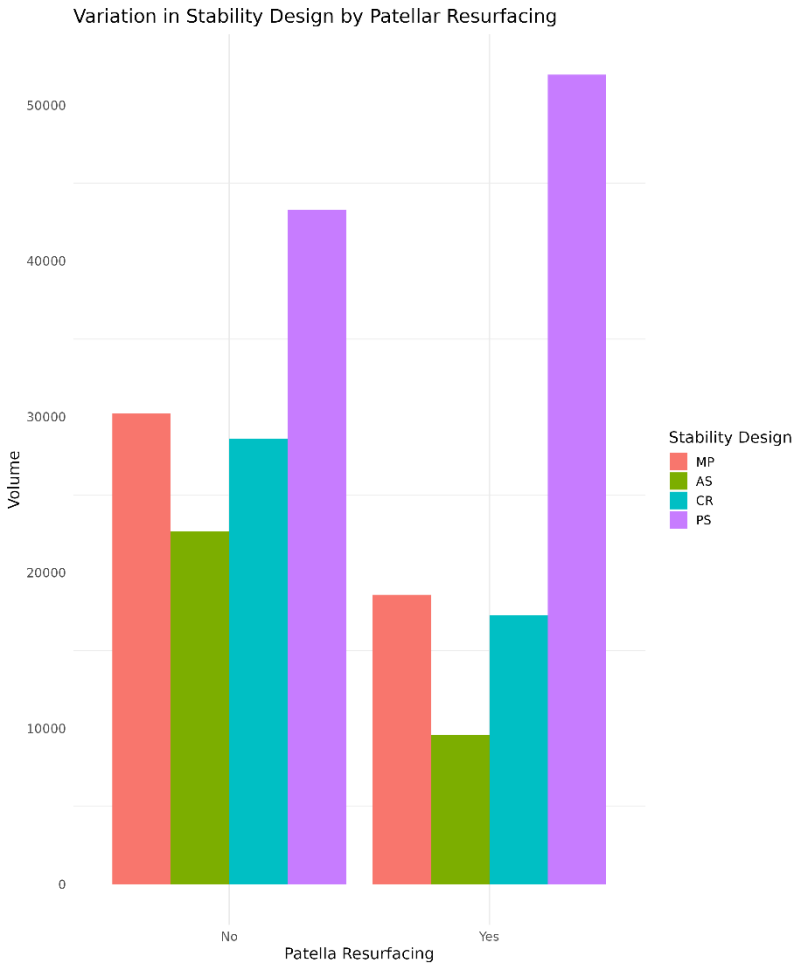


Figure 4.1: Patellar resurfacing and stability design cumulative utilization over the study period (2019-2023). PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

increase historically attributed to "PCL-retaining" designs as a whole, true CR utilization actually declined over the study period, from 24.0% in 2019 to 17.7% in 2023 ($\chi^2 = 791.2$, r = 0.060, $r^2 = 0.004$).

All eight patellar resurfacing-stability design combinations showed statistically significant temporal trends over the study period (all $p < 0.001$), though with small effect sizes (Fig. 4.4). The strongest trend was observed for MP without patellar resurfacing ($\chi^2 = 7702.8$, r = 0.186), followed by PS with patellar resurfacing ($\chi^2 = 2848.6$, r = 0.113) and MP with patellar resurfacing ($\chi^2 = 1118.2$, r = 0.071). CR without patellar resurfacing showed the weakest trend ($\chi^2 = 37.3$, $p < 0.001$, r = 0.013), consistent with the comparatively flat trajectory of CR utilization noted above. Overall, growth in MP utilization, both with and without patellar resurfacing, was the dominant driver of change in stability design combinations over the study period.

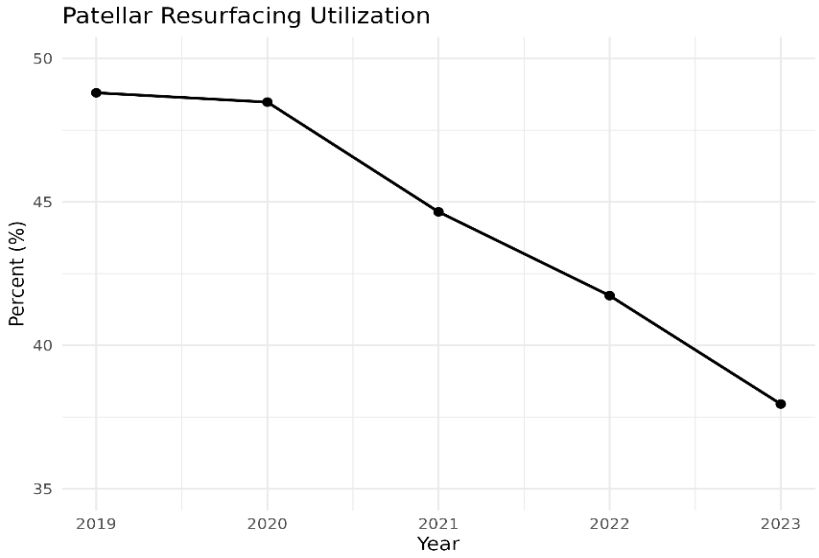


Figure 4.2: Patellar resurfacing rates across fiscal years.

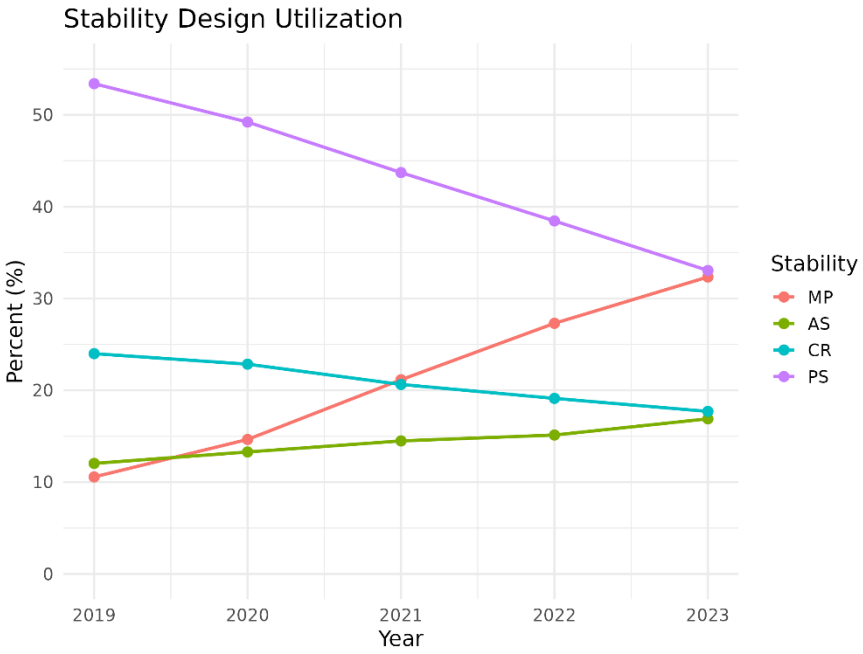


Figure 4.3: TKA stability design (PCL-retaining and sacrificing) utilization rates across fiscal years.PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

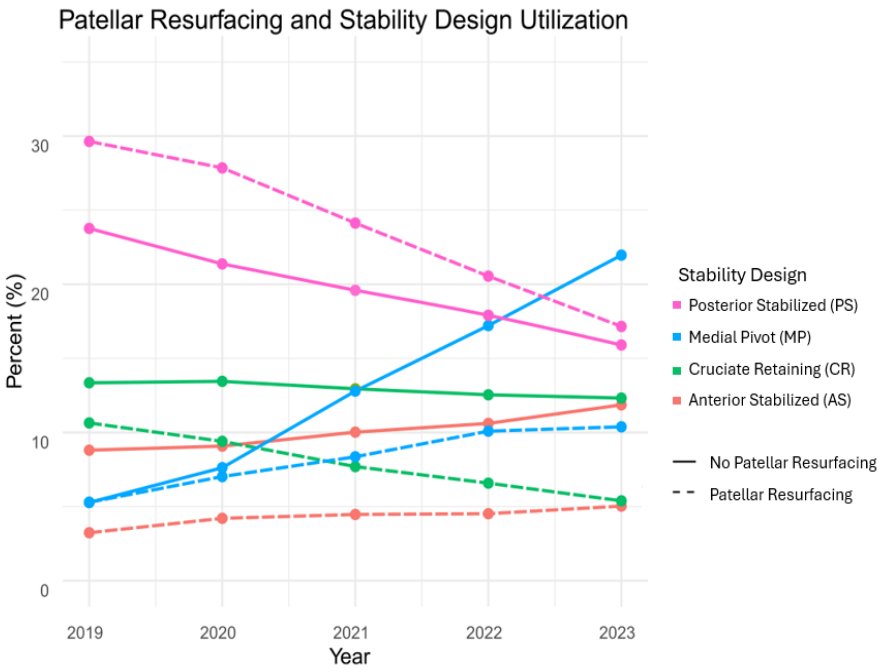


Figure 4.4: Patellar resurfacing and implant stability design combination utilization rates across fiscal years. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

4.4.4 Provincial Variation in Patellar Resurfacing and Stability Design

Significant variation in patellar resurfacing rates was observed across provinces (χ^2 = 3651.8, df = 6, p < 0.001, Cramér's V = 0.128; Table 4.2, Fig. 4.5). Manitoba reported the highest rate (63.3%) and Newfoundland and Labrador the lowest (19.0%), with most other provinces falling between 41% and 51%. Pairwise Bonferroni-corrected comparisons (adjusted α = 0.00238) found all province pairs except Ontario-Alberta (χ^2 = 2.12, p = 0.145) to differ significantly, with the largest effect sizes involving Newfoundland and Labrador (e.g., vs. Manitoba: χ^2 = 1553.0, Cramér's V = 0.206; vs. Ontario: χ^2 = 1012.0, Cramér's V = 0.092).

A multivariable logistic regression model, adjusting for age at surgery, sex, and fiscal year, showed that significant provincial variation in patellar resurfacing persisted after adjustment, with odds ratios expressed relative to the weighted national average (Saskatchewan excluded; see Statistical Analyses, Table 4.3). Manitoba had the highest adjusted odds of patellar resurfacing (OR 2.297, 95% CI: 2.215-2.382), followed by British Columbia (OR 1.103, 95% CI: 1.085-1.122). Ontario, the omitted reference province under weighted effects coding, had odds slightly below the national average (OR 0.944, 95% CI: 0.936-0.951), as did Alberta (OR 0.923, 95% CI: 0.901-0.945). Nova Scotia did not differ significantly from the national average (OR 0.996, 95% CI: 0.957-1.037, p = 0.841), while Newfoundland and Labrador had the lowest adjusted odds (OR 0.311, 95% CI: 0.290-0.334). Each additional year of age (OR 1.003, 95% CI: 1.002-1.004) and each successive fiscal year (OR 0.892, 95% CI: 0.887-0.897) were also independently associated with patellar resurfacing, while male sex was associated with lower odds (OR 0.802, 95% CI: 0.788-0.816) (all p < 0.001 unless otherwise noted). This model showed modest fit (McFadden's pseudo-R^2 = 0.019; AUROC = 0.588). A supplementary model including a province × fiscal year interaction term confirmed that this heterogeneity was statistically significant (likelihood ratio χ^2 test, p < 0.001) but only marginally improved model fit (pseudo-R^2 = 0.020; AUROC = 0.589), indicating that the temporal decline in patellar resurfacing was broadly consistent across provinces.

Table 4.3: Logistic regression: predictors of patellar resurfacing. Province odds ratios (OR) are relative to the weighted national average (weighted effects coding); Saskatchewan excluded from the model due to sparse anterior-stabilized counts causing separation.

Predictor	**OR**	**95% CI**	
		Lower	**Upper**
Age at surgery (per year)	1.003	1.002	1.004
Male sex (ref: female)	0.802	0.788	0.816
Alberta (vs. national avg.)	0.923	0.901	0.945
British Columbia	1.103	1.085	1.122
Manitoba	2.297	2.215	2.382
Newfoundland & Labrador	0.311	0.290	0.334
Nova Scotia	0.996	0.957	1.037
Fiscal year (per year, centered)	0.892	0.887	0.897
Ontario*	0.944	0.936	0.951

*Ontario OR and confidence intervals (CI) recovered via weighted sum-to-zero constraint; 95% CI was estimated using the delta method and reflects uncertainty propagated through the linear combination of directly estimated provincial coefficients.

Stability design also differed significantly across provinces ($\chi^2 = 33{,}160$, df = 18, $p < 0.001$, Cramér's V = 0.223, moderate effect; Table 4.2, Fig. 4.6). PS use ranged from 18.2% in Saskatchewan to 84.1% in Manitoba, while MP use ranged from 1.0% in Nova Scotia to 29.7% in British Columbia (individual AS and MP counts for Manitoba and Saskatchewan were suppressed per CIHI disclosure rules; Table 4.2).

A multinomial logistic regression model with CR as the reference category (adjusting for age, sex, fiscal year, and province; Saskatchewan excluded due to sparse counts) identified significant independent predictors of AS, MP, and PS use relative to CR (Table 4.4). Each successive fiscal year was associated with increased odds of AS (OR 1.212, 95% CI: 1.200-1.224) and, most markedly, MP (OR 1.447, 95% CI: 1.433-1.462) relative to CR, and

with decreased odds of PS relative to CR (OR 0.962, 95% CI: 0.954-0.969), mirroring the temporal patterns described above. Provincial variation relative to the weighted national average was substantial for all three comparisons, most notably for MP, where Nova Scotia (OR 0.037, 95% CI: 0.031-0.046) and Newfoundland and Labrador (OR 0.205, 95% CI: 0.184-0.227) had markedly lower odds and British Columbia (OR 2.413, 95% CI: 2.347-2.482) had markedly higher odds than the national average. Older age was associated with modestly lower odds of AS, MP, and PS relative to CR (all OR < 1, $p < 0.001$), and male sex was associated with modestly higher odds of MP and PS relative to CR (both $p < 0.05$) but lower odds of AS (OR 0.948, 95% CI: 0.920-0.976, $p < 0.001$). Ontario, which was omitted under weighted effects coding, had estimated odds ratios close to 1.00, indicating minimal deviation from the national weighted average. This model showed modest fit (McFadden's pseudo-$R^2 = 0.059$; multiclass AUROC = 0.632). As with the patellar resurfacing model, a supplementary model including a province $\times$ fiscal year interaction term was statistically significant but produced only a small further improvement in fit (McFadden's pseudo-$R^2 = 0.062$; multiclass AUROC = 0.635).

Table 4.4: Multinomial logistic regression: predictors of stability design relative to the cruciate-retaining (CR) reference category. Province odds ratios (OR) expressed relative to the weighted national average (weighted effects coding); Saskatchewan excluded due to sparse anterior-stabilized counts.

	Anterior Stabilized			**Medial Pivot**			**Posterior Stabilized**		
Predictor	**OR**	**95% CI**		**OR**	**95% CI**		**OR**	**95% CI**	
		Lower	**Upper**		**Lower**	**Upper**		**Lower**	**Upper**
Age at surgery (per year)	0.986	0.984	0.988	0.990	0.988	0.992	0.997	0.996	0.998
Male sex (ref: female)	0.948	0.920	0.976	1.030	1.001	1.060	1.026	1.002	1.050
Alberta (vs. national avg.)	0.998	0.952	1.046	1.038	0.993	1.084	1.772	1.714	1.832

Predictor	Anterior Stabilized			Medial Pivot			Posterior Stabilized		
	OR	95% CI		OR	95% CI		OR	95% CI	
		Lower	Upper		Lower	Upper		Lower	Upper
British Columbia	2.035	1.976	2.096	2.413	2.347	2.482	0.959	0.936	0.983
Manitoba	0.155	0.129	0.187	0.875	0.800	0.957	4.776	4.484	5.087
Newfoundland & Labrador	0.361	0.330	0.396	0.205	0.184	0.227	0.356	0.334	0.379
Nova Scotia	0.844	0.794	0.897	0.037	0.031	0.046	0.792	0.756	0.829
Ontario*	0.974	–	–	0.999	–	–	0.812	–	–
Fiscal year (per year, centered)	1.212	1.200	1.224	1.447	1.433	1.462	0.962	0.954	0.969

*Ontario coefficient recovered via weighted sum-to-zero constraint of weighted effects coding. Delta-method 95% CIs for these recovered multinomial coefficients could not be reliably estimated and are therefore not reported; Ontario estimates should be interpreted as point estimates only. Ontario-referenced estimates with CIs are provided in the conventional reference-coded sensitivity model (Section D.3).
Abbreviations: AS = anterior-stabilized; MP = medial-pivot; PS = posterior-stabilized; CI = confidence interval.

Examination of the patellar resurfacing-stability design combinations showed that, in most provinces, TKAs using PS without patellar resurfacing or CR without patellar resurfacing were among the most common configurations (Fig. 4.7). In Manitoba, however, the large majority of TKAs were PS with patellar resurfacing, consistent with that province's markedly elevated adjusted odds of both patellar resurfacing and PS use reported above.

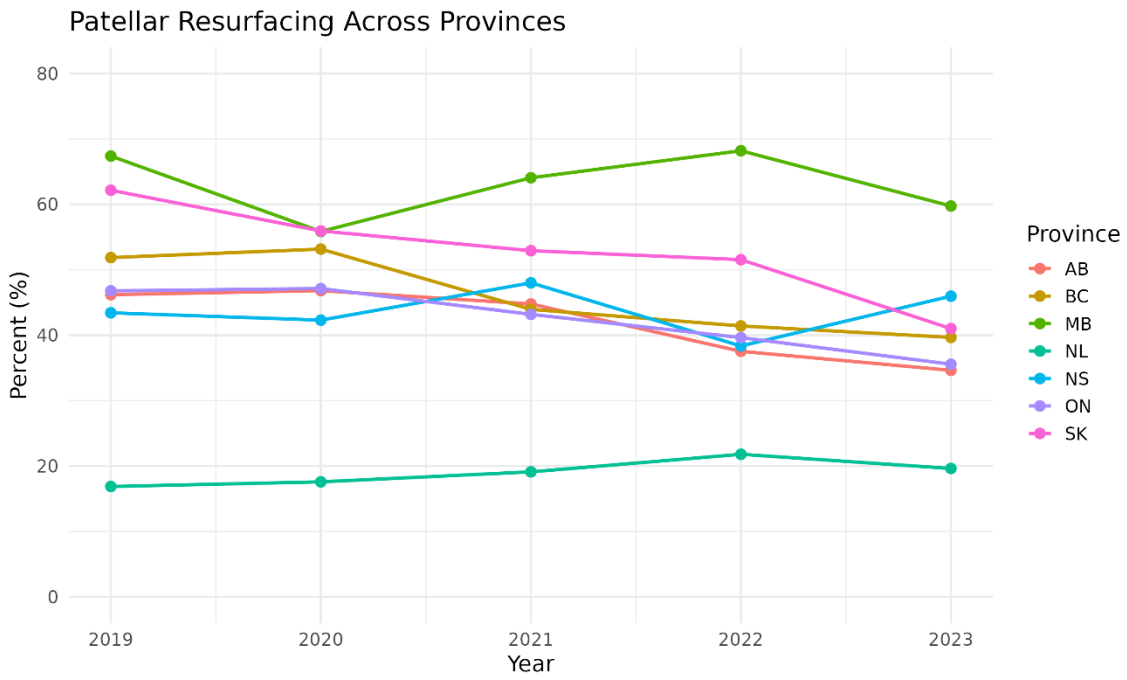


Figure 4.5: Patellar resurfacing utilization trends across provinces (2019-2023). ON = Ontario, AB = Alberta, BC = British Columbia, MB = Manitoba, NL = Newfoundland & Labrador, NS = Nova Scotia, SK = Saskatchewan.

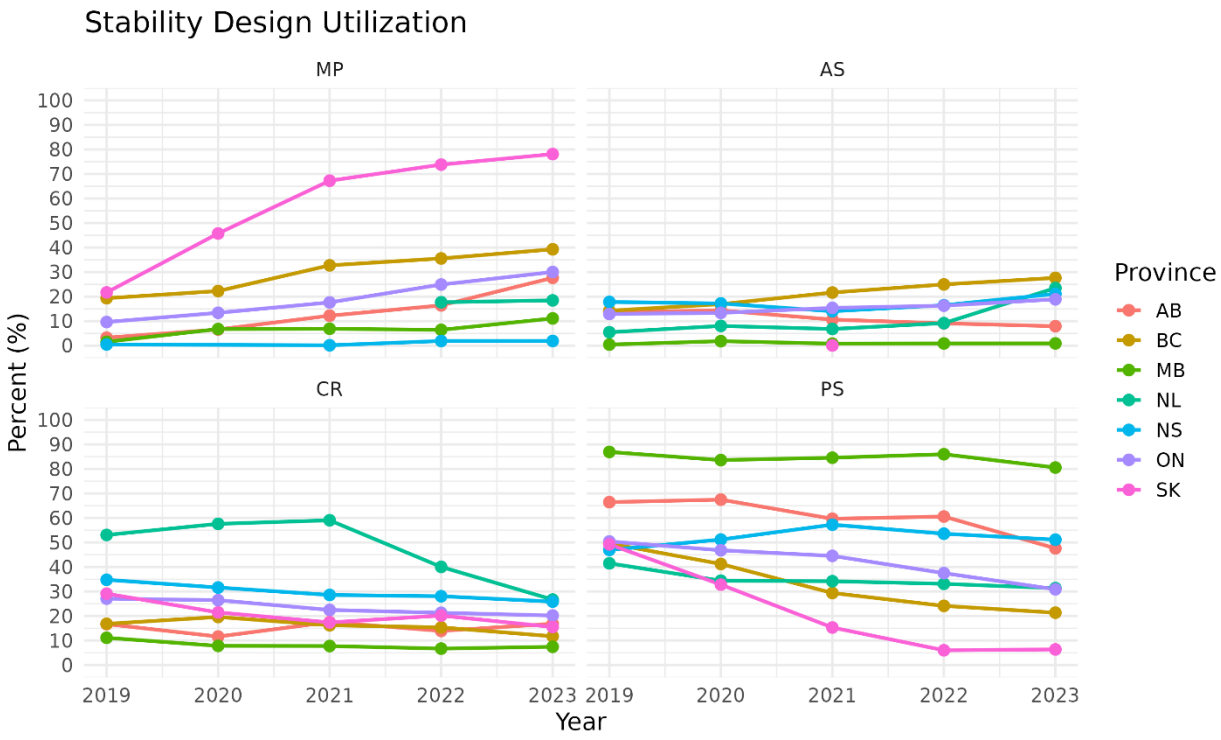


Figure 4.6: Stability design utilization across provinces (2019-2023). ON = Ontario, AB = Alberta, BC = British Columbia, MB = Manitoba, NL = Newfoundland & Labrador, NS = Nova Scotia, SK = Saskatchewan. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

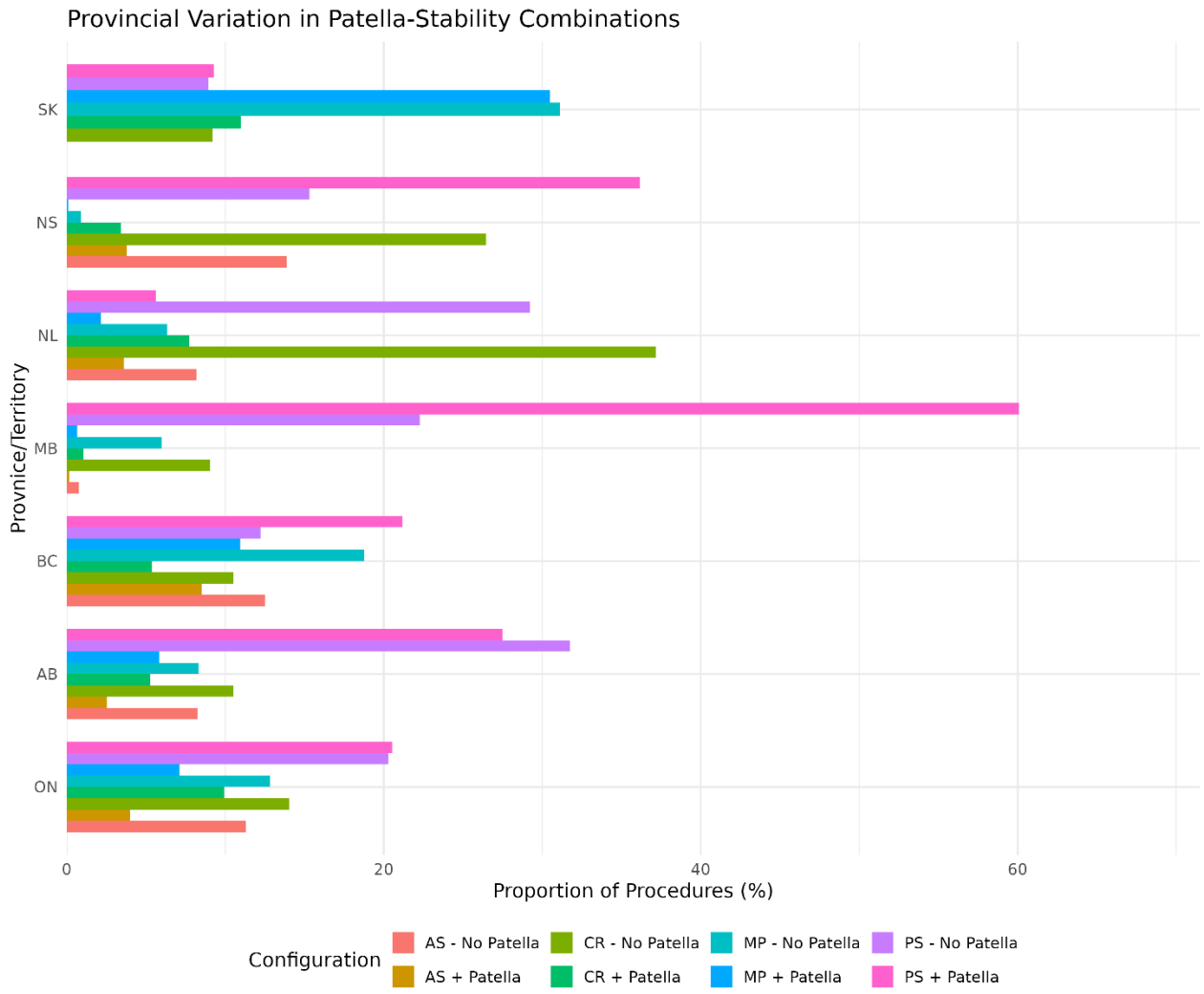


Figure 4.7: Patellar resurfacing and stability design utilization across provinces. ON = Ontario, AB = Alberta, BC = British Columbia, MB = Manitoba, NL = Newfoundland & Labrador, NS = Nova Scotia, SK = Saskatchewan. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

4.4.5 Patient Demographic Associations

Patellar resurfacing rates differed significantly by both sex and age group. Among female patients, 46.2% received patellar resurfacing compared with 40.6% of male patients (χ^2 = 686.3, df = 1, p < 0.001, Cramér's V = 0.056), consistent with the male-sex coefficient in the adjusted regression model above. A statistically significant but negligible (based on effect size) association was also observed between age group and patellar resurfacing (χ^2 = 18.6, df = 4, p < 0.001, Cramér's V = 0.009), with resurfacing rates ranging narrowly from 43.1% to 44.4% across age groups.

Stability design selection also varied significantly, though again negligibly, by sex (χ^2 = 36.7, df = 3, p < 0.001, Cramér's V = 0.013) and age group (χ^2 = 172.6, df = 12, p < 0.001, Cramér's V = 0.016). AS use declined modestly with age (15.2% in patients under 50 vs. 13.0% in patients 80 and older), while CR use increased slightly (18.3% vs. 20.9%); MP (21.9-23.1%) and PS (42.6-44.2%) use were comparatively stable across age groups. The distribution of the eight patellar resurfacing-stability design combinations also differed significantly by sex (χ^2 = 853.2, df = 7, p < 0.001, Cramér's V = 0.062) and age group (χ^2 = 253.8, df = 28, p < 0.001, Cramér's V = 0.017), though both effect sizes and absolute differences were negligible (Fig. 4.8, 4.9). As reported above, the multivariable models similarly found only modest associations between age or sex and either surgical decision after adjustment, consistent with these bivariate findings.

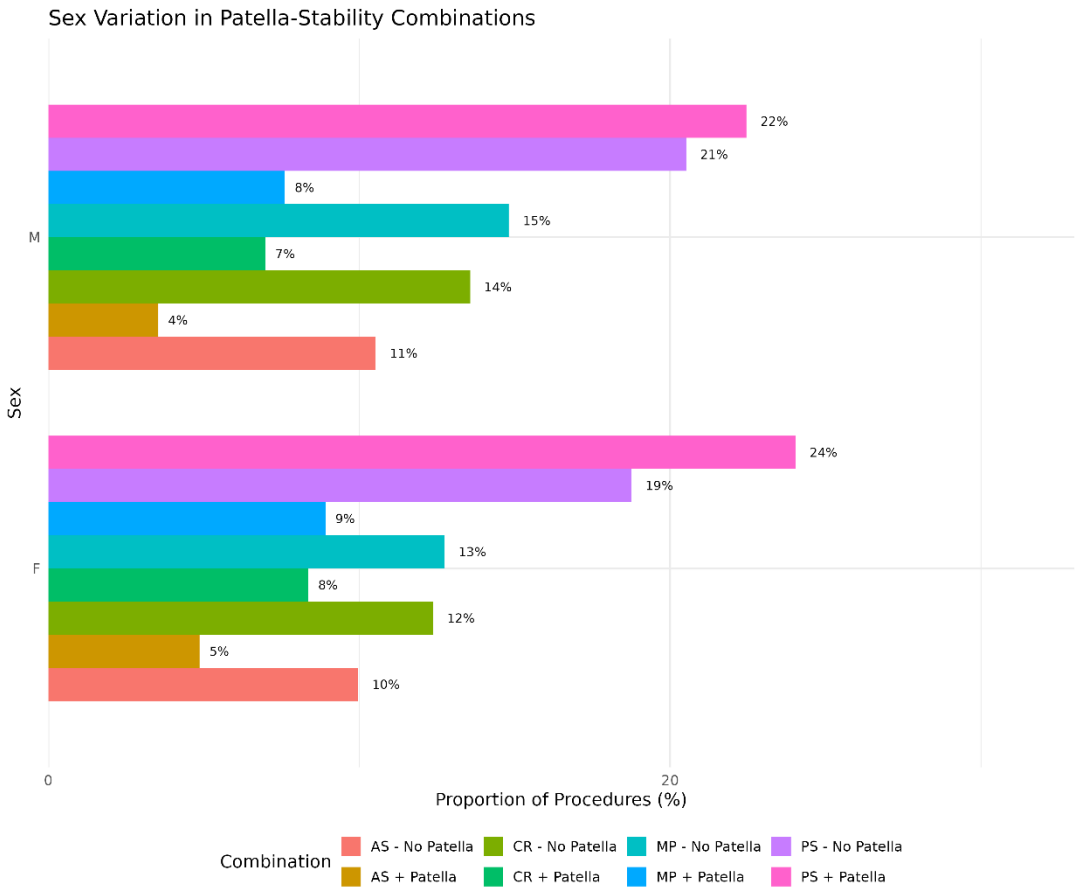


Figure 4.8: Patellar resurfacing and stability design utilization by patient sex. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

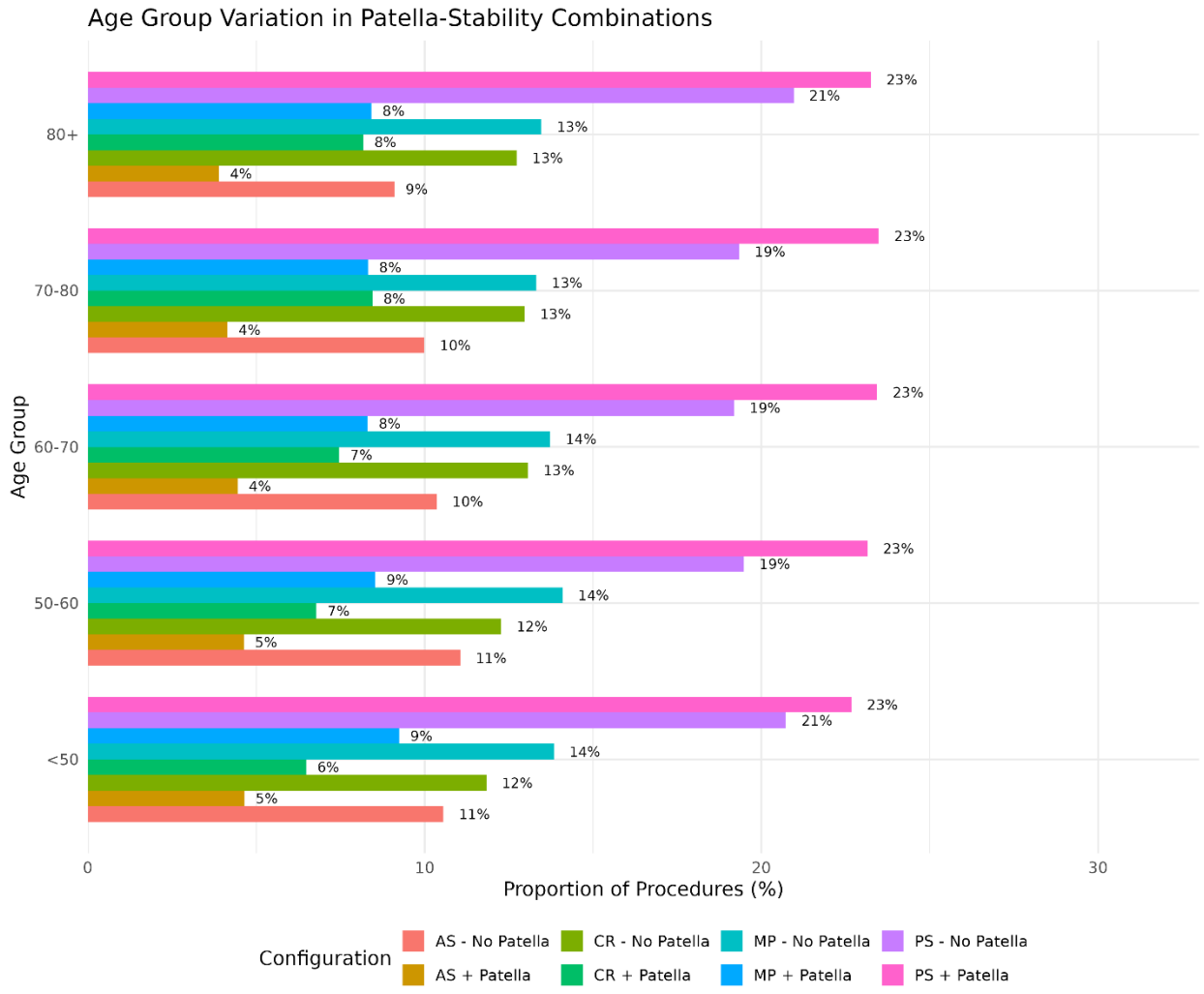


Figure 4.9: Patellar resurfacing and stability design utilization across patient age-groups. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot.

4.4.6 Implant System Utilization

Variability across implant systems was apparent across patellar resurfacing and stability design combinations (Fig. 4.10). Zimmer Persona and Stryker Triathlon systems were used in a large proportion of procedures across all combinations during the study period, accounting for 68-90% of procedures in each resurfacing/stability group. The Smith & Nephew Legion system was present exclusively in PS procedures with or without patellar resurfacing, and is not among the top 5 implant systems used in either CR, AS, or MP groups. Similarly, the Smith & Nephew Genesis system was only among the most-used systems in the PS-with-patellar-resurfacing group, and the MicroPort Evolution was only among the top implant systems used in MP procedures (with or without patellar resurfacing).

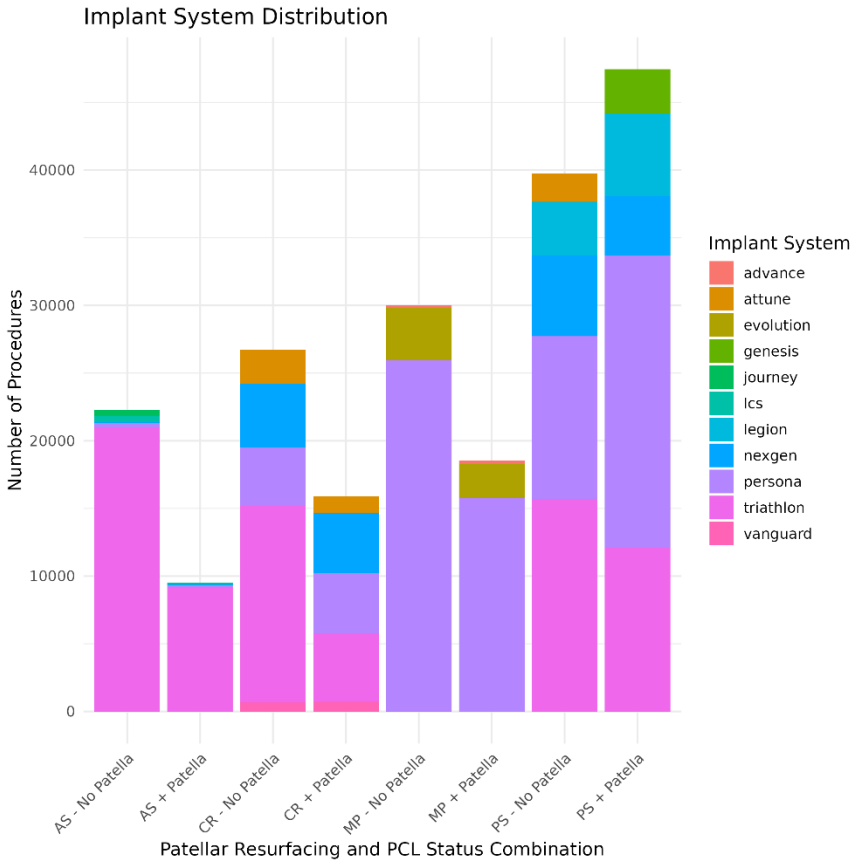


Figure 4.10: Implant system distribution of the top 5 systems by patellar resurfacing and stability design. PS = posterior stabilized, AS = anterior stabilized, CR = cruciate retaining, MP = medial pivot. The models reported included: Persona, NexGen, and Vanguard from Zimmer Biomet (Warsaw, IN, US), Triathlon from Stryker (Mahwah, NJ, US), Legion and Genesis from Smith & Nephew (London, United Kingdom), Evolution and Advance from MicroPort (Shanghai, China), and Attune and LCS from DePuy Synthes (Loughbeg Ringaskiddy, CK, IE).

4.5 Discussion

This analysis of Canadian Joint Replacement Registry TKA data from 2019 to 2023, disaggregating implant stability design into its four constituent categories (CR, PS, MP, AS) rather than the binary CR/PS framework used in most prior registry analyses, showed that national rates of both patellar resurfacing and PS implant designs declined significantly over the study period. However, this apparent shift away from PS was driven predominantly by rapidly increasing MP utilization rather than an increase in CR designs, which modestly declined in relative use. Only when MP and AS are collapsed into a combined "CR" category, as in many registry reports including CJRR's own national summaries, does the data appear to show a straightforward move toward PCL-retaining designs. However, this grouped, "Minimally Stabilized" representation may overestimate true cruciate-retaining procedures, as MP and AS designs can be used with or without PCL resection, and the surgical data needed to validate PCL resection is not recorded in the CJRR. Patellar resurfacing and stability design also showed a small association (Cramér's V = 0.195), with PS the most common design regardless of resurfacing status but MP consistently the second most common design when the patella was resurfaced. These decisions were modelled as separate multivariable regressions rather than as covariates of one another, since both are surgical choices made at the time of the procedure without a definable causal ordering between them; their association is therefore best characterized descriptively, as above, rather than through a directional regression coefficient.

Between 2019 and 2023, Canadian patellar resurfacing rates declined from 48.8% to 38.0%. This aligns with the notable decrease in patellar resurfacing from 45.2% to 33.0% reported in the 2021-2022 and 2024-2025 CJRR reports [25,26]. Compared to other arthroplasty registries, Canada has among the lowest rates of patellar resurfacing in TKA. Based on their annual reports, the American, Dutch, and Australian registries all report resurfacing rates over 80% [6,7,32]. Sweden, however, remains the lowest in patellar resurfacing, reporting 3% patella use in TKA in 2023 [27]. Thus, Canada shows a unique middle-ground trend in patellar resurfacing among the global registry landscape.

Interestingly, Canada's shift away from patellar resurfacing contradicts findings from

the CJRR that TKA without patellar resurfacing had significantly higher revision rates than those with resurfacing (for both PS and CR implants), with adjusted hazard ratios of 1.12 and 1.19, respectively [25]. This paradox may suggest that revision rates alone do not fully capture the outcomes surgeons and patients prioritize. Functional outcome scores and patient-reported outcome measures (PROMs) show more mixed results, with several studies reporting no significant differences between resurfaced and non-resurfaced TKA [12,13], and others suggesting that patella-friendly femoral designs may adequately address anterior knee pain without formal resurfacing [33–35]. Surgeons may therefore be responding to a broader and more heterogeneous evidence base than revision rates alone. Moreover, this contradiction may reflect a lag between registry-level revision evidence and evolving surgical practice; thus, the registry revision risk differentials may not be generalizable to all modern implants.

Over the study period, PS design utilization decreased from 53.4% in 2019 to 33.1% in 2023. This was the steepest absolute decline of any single stability category, while CR utilization, once isolated from MP and AS, declined only modestly (24.0% to 17.7%) and MP utilization more than tripled (10.6% to 32.3%), and showed the greatest acceleration of any stability design nationally, nearly matching PS in relative use by 2023. This finding reframes the shift observed in prior binary analyses: rather than reflecting increased confidence in traditional PCL-retaining (CR) mechanics, the Canadian data suggest surgeons increasingly adopted medial-pivot kinematics specifically. This shift aligns with the lower reported revision rates for CR relative to PS across many national arthroplasty registries (Canada, the US, and Australia all report higher CPR with PS designs than CR designs) [6,8,25], and with emerging registry evidence that MP designs achieve revision rates comparable to CR when the patella is resurfaced, though somewhat higher when it is not [6,8]. Canada's rapid uptake of MP designs specifically, rather than a generic move toward PCL preservation, is consistent with, and potentially suggestive of, evolving surgeon confidence in medial-pivot kinematics as a distinct alternative to both traditional CR and PS philosophies. Since MP (and AS) designs can be used with either PCL resection or preservation, the increased MP utilization does not necessarily indicate increased PCL retention. Retrospective, observational studies on MP TKA outcomes have reported mixed

PCL management, with PCL preservation ranging from 23 to 75% of the study cohorts [36–39]. Thus, without surgical PCL management data (currently not collected through the CJRR), the true rates of PCL resection among Canadian TKAs cannot be determined.

Formal trend testing of each of the eight patellar resurfacing-stability design combinations individually revealed that all showed statistically significant changes over the study period. The strongest trend was observed for MP without patellar resurfacing (increasing), followed by PS with patellar resurfacing (decreasing) and MP with patellar resurfacing (increasing); CR without patellar resurfacing (decreasing) showed the weakest, though still significant, trend. This pattern further suggests that MP growth, rather than an increase in traditional CR use that would have otherwise been reported under the "Minimally Stabilized" CR, MP, and AS grouping, was the dominant driver of Canada's apparent shift away PS designs over the study period.

The greater proportion of PS procedures performed with patellar resurfacing than without (Fig. 4.1), while MP, CR, and AS designs showed lower rates of use with patellar resurfacing, may implicate various factors suggested in the literature. For one, implant system design may promote bundling of these decisions: certain femoral component geometries are specifically designed for use with or without patellar resurfacing based on their trochlear conformity [33,40], and some implant systems have outcome literature recommending routine resurfacing when used [41]. This is supported by the implant system data reported here, in which the Smith & Nephew Genesis system was only reported among PS procedures with patellar resurfacing but was absent from the other groups, suggesting that system-level factors promote joint selection of stability design and patellar resurfacing. Similarly, Stryker Triathlon models were absent from the MP groups (with and without patellar resurfacing) as this manufacturer has yet to release a medial pivot insert. Thus, manufacturer and procurement practices may also influence these surgical decisions. Procurement in Canada is conducted at the hospital level; thus, any hospital solely supplied by Stryker would not have access to MP options for their patients. Clinical evidence may also reinforce this pattern: PS implants with patellar resurfacing have been associated with better clinical outcomes than those without [6,42], which may lead surgeons using PS designs to resurface routinely. Another factor, and perhaps most influential given the modest ex-

planatory power of the patient- and province-level variables examined in this study, may be individual surgeon preference. Registry-based surgeon-level analyses support this: an analysis of 422 surgeons from the Australian registry found that ~28% resurfaced the patella in more than 90% of cases, while ~16% did so in less than 10% of cases, demonstrating highly polarized individual practice patterns [3]. A separate Canadian analysis reported similarly fixed preferences for stability design, with ~34% of surgeons using PS implants in over 90% of cases and another 34% using them in fewer than 10%, and, reported that among surgeons who resurfaced the patella in over 90% of cases, PS implants were used in 60% of procedures, demonstrating that these two preferences are often linked within individual surgeons [43]. Conversely, the growing adoption of patella-friendly femoral designs may contribute to the decoupling of these decisions over time, as optimized trochlear geometry reduces the clinical rationale for routine resurfacing regardless of stability design [33–35,44–46].

Significant provincial variation was observed for both patellar resurfacing (Cramér's V = 0.128) and stability design (Cramér's V = 0.223), both representing small-moderate but broad-based effects rather than variation driven solely by isolated outlier provinces. Manitoba and Newfoundland and Labrador remained the most extreme provinces at either end of the resurfacing spectrum, and both showed persistent deviations from the national average even after multivariable adjustment for age, sex, and fiscal year. Of note, the majority of TKAs in Manitoba and Newfoundland and Labrador are generally performed at a small number of institutions, so these patterns may reflect the practices of a limited number of surgeons or centres rather than broader provincial health-system differences, making direct comparison with high-volume, multi-institution provinces such as Ontario (~51% of national TKA volume) challenging.

The multivariable regression models confirmed that provincial variation in both patellar resurfacing and stability design persisted after adjustment for age, sex, and fiscal year, indicating that these differences are not necessarily artifacts of differing patient case-mix or timing across provinces. Both models showed modest fit (patellar resurfacing: McFadden's pseudo-R^2 = 0.019, AUROC = 0.588; stability design: McFadden's pseudo-R^2 = 0.059, multiclass AUROC = 0.632), indicating that the measured patient- and province-level

predictors together explain only a minimal proportion of the variance in these surgical decisions and correctly discriminate outcomes only somewhat better than chance. Rather than reflecting a limitation of the models, this suggests that the dominant sources of variation in the selection of patellar resurfacing and stability design are factors unmeasured in this analysis. Perhaps, some of these unmeasured factors may include surgeon preference and institutional practice. This interpretation is consistent with the negligible demographic effect sizes reported, the persistent provincial outliers after adjustment, and surgeon-level analyses from other registries demonstrating that individual surgeon practice patterns are a primary determinant of patellar resurfacing decisions [3,43].

While several statistically significant differences in patellar resurfacing and stability design by patient age or sex were observed, effect sizes were consistently negligible (Cramér's $V \leq 0.06$ for all comparisons). In contrast, other registry analyses, such as one from the Dutch LROI, have reported significant age and sex differences in patellar resurfacing. Specifically, they reported that females and younger patients were more likely to have their patella resurfaced [47]. The discrepancy between the Dutch and Canadian findings may suggest that in Canadian TKA, patellar resurfacing and stability design selection are driven primarily by surgeon- and institution-level factors rather than patient characteristics.

These findings have several implications. The declining trends in PS use and rising MP use, alongside a comparatively stable rate of true CR utilization, suggest that Canadian surgeons are increasingly adopting medial-pivot kinematics as an alternative to both traditional cruciate-retaining and posterior-stabilized philosophies, a trend obscured by binary CR/PS reporting frameworks used elsewhere. The pace and consistency of this shift varied meaningfully, though modestly, across provinces, which, combined with the persistence of extreme outlier provinces after adjustment, may suggest a need for national consensus guidelines or benchmarking through CJRR to better understand and, where appropriate, reduce practice variation, particularly given the current absence of strong comparative outcome evidence specific to MP designs in the Canadian population. Moreover, the association between patellar resurfacing and stability design, while descriptive rather than causal in this analysis, suggests these decisions should continue to be considered and reported jointly in future registry work, including disaggregated reporting of MP and AS

designs, rather than collapsed into a binary CR/PS or "minimally stabilized" framework that may obscure clinically meaningful trends such as the rapid rise of MP utilization documented here.

Several limitations exist for this study. The study period was limited to 5 years (2019 to 2023); thus, trends beyond this window were not reported and may not be consistent with those described here. As noted, this analysis did not capture surgeon- or institution-level factors that may influence patellar resurfacing or stability design decisions, reflected by the modest fit of both regression models (patellar resurfacing: pseudo-$R^2 = 0.019$, AUROC = 0.588; stability design: pseudo-$R^2 = 0.059$, multiclass AUROC = 0.632). Moreover, procedures with patellar resurfacing were identified by the presence of a patellar component in a given procedure; thus, if the patellar component was not recorded, the procedure would be incorrectly classified as without patellar resurfacing, potentially underestimating patellar resurfacing rates. Procedure codes could not validate patellar resurfacing, as nearly half of the CJRR submissions did not include these identifiers. Similarly, PCL management (resection or preservation) could not be determined for MP and AS procedures (where PCL resection is optional), as the CJRR does not currently collect this surgical information. However, future analyses should consider PCL management where data are available, describe and account for differences in surgical philosophies regarding soft-tissue management in TKA. Patellar resurfacing and stability design were modelled as separate multivariable outcomes rather than as covariates of one another, since both represent surgical decisions made at the time of the procedure without a definable causal ordering; their association is therefore reported descriptively (Cramér's V) rather than through a directional regression coefficient, and future work using surgeon-level or instrumental-variable approaches, as employed in other registries [32], may be better positioned to characterize this relationship causally. Provincial comparisons should also be interpreted with some caution, as a small number of high-volume institutions may disproportionately influence the results for lower-volume provinces such as Manitoba and Newfoundland and Labrador. Stability design was classified using implant catalogue number and manufacturer data, and medial pivot and medial congruent inserts were considered synonymous; despite a shared kinematic aim, these designs differ slightly in femoral geometry and degree of constraint and may differ

in clinical performance. Moreover, monoblock tibial components were retained in the primary analysis. A sensitivity analysis excluding monoblock components produced generally unchanged results (Section D.1). Additional limitations include the absence of clinical outcome data, precluding any direct linkage between the reported trends and patient outcomes, and the absence of comorbidity or disease severity data, which limits the ability to adjust for case complexity and may influence both patellar resurfacing and stability design decisions.

4.5.1 Conclusion

This study characterized national trends in patellar resurfacing and implant stability design in Canadian TKA from 2019 to 2023, disaggregating stability design into four categories (CR, PS, MP, AS) rather than the binary CR/PS framework used in most prior work. Patellar resurfacing and PS rates both declined significantly. The shift in stability design was driven predominantly by MP utilization, which more than tripled. PS remained the most common design overall, with MP consistently second among resurfaced procedures, and the two decisions showed a small descriptive association. Provincial variation in both decisions was small but broad-based, with Manitoba and Newfoundland and Labrador the most extreme provinces even after adjustment. These findings support reporting stability design using its full range of categories, including MP and AS, rather than collapsing them into a binary or minimally-stabilized framework that obscures trends such as the rapid rise of MP, and suggest value in national benchmarking through the CJRR.

4.6 References

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Chapter 5

Manufacturer Trends

5.1 Abstract

5.1.1 Background

Total knee arthroplasty (TKA) volumes have continued to rise, yet manufacturer- and model-level implant utilization has rarely been reported in Canada, unlike in registries such as the American, Australian, and New Zealand Joint Registries. Given Canada's decentralized, hospital-level procurement system, understanding national and provincial implant market trends may inform equitable access and future negotiating leverage. Therefore, this study aimed to characterize the distribution of TKA manufacturers and models in Canada and quantify TKA market concentration.

5.1.2 Methods

This retrospective cohort study used de-identified Canadian Joint Replacement Registry (CJRR) records from 2019-2023 for patients aged 18 years or older undergoing primary TKA. Manufacturer and model unit market share trends were assessed using Cochran-Armitage trend tests, Pearson's chi-squared tests of independence, and linear regression,

stratified by province and fixation (cemented/cementless). Market concentration was quantified using the Herfindahl-Hirschman Index (HHI).

5.1.3 Results

Among 219,386 TKA records, Zimmer and Stryker had the largest market shares, together accounting for 87% of cases by 2023. Over the 5-year study period, Zimmer's share increased significantly from 47.5% to 51.9% ($p<0.001$), while MicroPort declined from 4.9% to 1.7% ($p<0.001$). Manufacturer distribution varied significantly by province ($p < 0.001$, Cramer's $V=0.27$), though model-level construct use did not differ meaningfully across provinces, indicating consistent national model preferences within manufacturer portfolios. National market concentration increased over the study period (HHI 3,604 to 3,962), with several provinces reaching near single-manufacturer concentration. The cementless market was especially concentrated, with Stryker's Triathlon Tritanium construct alone comprising roughly 60% (cruciate retaining) and 30% (posterior stabilized) of cementless cases, compared with a more evenly distributed cemented market led by Zimmer's Persona system, whose cemented CR construct share nearly tripled (12.5% to 32.3%).

5.1.4 Conclusion

Canada's TKA implant market is highly concentrated and increasingly dominated by two manufacturers, particularly within the cementless fixation market. While manufacturer use varies provincially, model preferences remain nationally consistent, highlighting opportunities for coordinated procurement strategies and continued implant-level surveillance.

5.2 Introduction

5.2.1 Knee Arthroplasty

Primary total knee arthroplasty (TKA) is the preferred procedure for advanced knee osteoarthritis and joint degradation. In this procedure, various implant components, including femoral, tibial, or patellar components, are inserted to replace the damaged bone and cartilage of the joint. Given the improved functionality and reduced pain associated with TKA, the volume of procedures has steadily increased over the last several decades and is predicted to continue rising [1,2]. While this increased uptake of TKA procedures will likely contribute to improved quality of life for many patients, differences in performance across implant models suggest that the benefits of increased utilization may also depend on selecting implants with demonstrated performance for individual patients [3–5]. Thus, monitoring trends in TKA utilization and understanding patterns in implant utilization are valuable for identifying whether patients are receiving implants associated with better clinical outcomes and ensuring that increases in TKA use are associated with improved patient outcomes.

5.2.2 Manufacturers and Models

Some of the predominant TKA implant suppliers globally include Depuy (DePuy Synthes, Warsaw, IN), Stryker (Stryker, Kalamazoo, MI), Zimmer/Biomet (Zimmer, Warsaw, IN), and Smith & Nephew (Smith and Nephew, Memphis, TN). These manufacturers offer a variety of TKA models, including both cemented and cementless fixation options. However, while the literature offers a variety of reports on the prevalence and clinical outcomes of general implant designs, such as cruciate-retaining, posterior-stabilization, or cementless fixation, reports on the utilization and performance of specific manufacturers and models are less common, especially from Canada. In fact, most national and even regional joint registries, including the American, Australian, New Zealand, and Michigan registries, report implant-level data, including model distributions and revision rates [3,4,6–8]. However, such information is scarcely reported in Canada. One of the few sources reporting

Canadian implant-level information is Chen et al. 2025, which reported aggregate volumes of cemented and cementless implants from 2012 to 2021 for four implant models (Stryker Triathlon, Zimmer Persona, Zimmer NexGen, DePuy Attune). Nevertheless, more detailed reporting of the Canadian implant landscape, including provincial, temporal, and model-level stratification, is needed to clarify national and provincial implant market trends and their possible implications for patient care.

5.2.3 Hospital Purchasing

Medical device procurement in Canada is generally decentralized at the hospital level [9]. While Canadian healthcare funding is predominantly derived from taxes, each province must independently manage the financing and organization of healthcare [9]. Overseen by the provincial government, each hospital or health center is then responsible for providing health services and purchasing the required medical equipment [9]. There are two main purchasing options for hospitals and healthcare providers: direct negotiation with distributors or utilizing a group purchasing organization (GPO), where a third-party company negotiates better prices and facilitates the purchase on behalf of a group of buyers (hospitals) [10]. While GPOs can enable hospitals to purchase necessary medical devices at a more competitive price, they may also contribute to market dominance by a smaller number of larger suppliers, as smaller or newer vendors often lack the established reputation or budget to compete with larger enterprises [13].

5.2.4 Objectives

This study aimed to investigate implant manufacturer and model trends across Canada, utilizing data from the Canadian Joint Replacement Registry from 2019 through 2023. This study examined regional and temporal variation in implant utilization, explored associations between manufacturer utilization, implant fixation, and patient demographics, investigated market concentration trends, and contextualized Canadian market trends against other national registries, including Australia and the United States. Given the decentral-

ized nature of healthcare delivery in Canada, this analysis may provide useful information to be leveraged in negotiating with implant manufacturers and may ultimately benefit Canadian patients.

5.3 Methods

5.3.1 Study Design

This retrospective cohort study used de-identified record-level data from the Canadian Joint Replacement Registry (CJRR) from the years 2019 through 2023. The data was provided through the Canadian Institute for Health Information's (CIHI) Graduate Student Data Access Program.

Parts of this material are based on data and information provided by the Canadian Institute for Health Information. However, the analyses, conclusions, opinions and statements expressed herein are those of the author and not necessarily those of the Canadian Institute for Health Information.

5.3.2 Study Population

The inclusion criteria for this study included: total knee arthroplasty procedure (with or without patellar resurfacing), minimum patient age of 18 years at the time of surgery, and the reporting province must have mandatory CJRR submission or minimum 70% submission coverage (Ontario (91.6%, mandatory reporting), British Columbia (94.3%, mandatory), Nova Scotia (94.1%, mandatory), Manitoba (99.5%, mandatory), Alberta (75.7%), Saskatchewan (96%), Newfoundland and Labrador (99.2%), and the Northwest Territories (97%)). See Section E.1 for the data inclusion/exclusion diagram.

5.3.3 Variables

The primary variables of interest were the implant manufacturer and model. Records missing manufacturer or model data for either the tibial baseplate or femoral components were excluded (Fig. E.1). Tibial components were considered as two distinct elements: the tibial baseplate (tray), which anchors to bone and determines fixation method, and the tibial insert, the polyethylene articulating surface that seats on the baseplate and determines the stability design of the construct (e.g., cruciate-retaining, posterior-stabilized, medial pivot, anterior-stabilized). The overall implant system manufacturer was determined by the femoral component manufacturer, as mixed-manufacturer systems accounted for $<$0.02% of records. Tibial and femoral model combinations were defined by the features of the components, such as femoral stability (constraint) design, and coatings, as specified by the device name registered in Health Canada's Medical Device Active License Listing (MDALL) database corresponding to the catalogue number recorded in the CJRR. For consistency in naming, if stability design or fixation were not included in the implant MDALL name, it was determined from manufacturer documentation corresponding to the recorded catalogue number. The model specification data was collected and drawn from the open-source implant reference library created in Chapter 2 to supplement the CJRR implant characteristic data.

Analyses of femoral and tibial baseplate model combinations were limited to those with at least 400 records (as done in the AOANJRR [3]; 88.9% coverage of the model-level analysis cohort). Tibial insert stability was examined separately for TKA systems with cruciate-retaining femoral components, again determined by catalogue number and associated manufacturer specification, since CR femoral components are compatible with inserts of more than one stability design. Femoral and tibial fixation (cemented or cementless) were each determined independently by catalogue number for their respective components; because fixation was assigned per component rather than per system, hybrid constructs (a cementless component paired with a cemented component) were not included in the fixation-disaggregated analyses due to model-level sample sizes below the 400-record threshold (see Section E.1 for hybrid counts).

Invalid mixed-manufacturer and stability constructs (e.g. cruciate retaining femoral component and posterior stabilized insert) were also excluded from analyses (Section E.1).

The primary manufacturers reported included: Zimmer Biomet (Warsaw, IN, US), Stryker (Mahwah, NJ, US), Smith & Nephew (London, United Kingdom), MicroPort (Shanghai, China), Corin (Gloucestershire, United Kingdom), Medacta International (Castel San Pietro, Switzerland), and DePuy (Loughbeg Ringaskiddy, CK, IE).

Other variables examined were reporting province, fiscal year (April 1 - March 31), and patient sex.

5.3.4 Statistical Analyses

Descriptive statistics summarized the distribution of manufacturers and models across fiscal years and provinces. The Cochran-Armitage proportions test assessed temporal trends in manufacturer and model market shares. Provincial and demographic differences, including patient sex, were tested with Chi-squared tests and Bonferroni-adjusted post-hoc comparisons. Bonferroni correction was applied only to these post hoc pairwise comparisons; omnibus chi-squared tests and Cochran–Armitage trend tests were reported unadjusted. A Pearson's chi-squared goodness-of-fit test was used to assess whether the national distribution of femoral–tibial model combinations differed from a uniform distribution. Effect size for Pearson's chi-squared tests of independence used Cramer's V effect size, interpreted according to Cohen's (1988) benchmarks, adjusted for table dimension by dividing the conventional thresholds for a 2 $\times$ k table (negligible $<$ 0.10, small 0.10 to $<$ 0.30, medium 0.30 to $<$ 0.50, large $\geq$ 0.50) by $\sqrt{(\min(n_{rows}, n_{columns}) - 1)}$ [18,40]. Effect size (r) for each Cochran-Armitage trend test was calculated as $r = \sqrt{(\chi^2/N)}$, where χ^2 is the test statistic, and N is the total number of records included in that comparison. Effect sizes were interpreted using established benchmarks for r (negligible $<$ 0.10; small 0.10 to $<$ 0.30; medium 0.30 to $<$ 0.50; large $\geq$ 0.50) [18,19]. Market concentration differences were evaluated using the Herfindahl-Hirschman Index (HHI) [20,21]. All statistical analyses were performed using R (v4.4.3.0).

Market share (by unit volume) was calculated as:

$$Unit\ Market\ Share = \frac{Total\ TKAs\ of\ the\ Manufacturer}{Total\ TKAs} \times 100$$

The HHI was calculated as:

$$HHI = \sum_{i=1}^{n} (S_i)^2$$

where S_i is the unit market share of the manufacturer/model i, as a whole number (e.g. 20 for 20%). The United States Department of Justice (DOJ) defines HHI thresholds to quantify market concentration; as Canada does not publish an equivalent implant-market concentration benchmark, these widely used thresholds are applied here as a general reference framework rather than a Canada-specific standard. HHI values below 1,000 are considered unconcentrated, HHI values between 1,000 and 1,800 indicate moderate concentration, and HHI values greater than 1,800 indicate high market concentration [22].

The manufacturer distributions and market concentration/HHI analyses described above were conducted at both the national level (aggregating all provinces) and, where cell sizes permitted, separately within each reporting province, to characterize provincial heterogeneity in implant utilization alongside national trends.

Linear regression quantified temporal trends in manufacturer market shares over fiscal years, with annual percentage-point market share as the outcome and fiscal year as the predictor; regression slopes (β) are reported as the estimated annual change in market share (percentage points per year).

To contextualize Canadian findings within the international literature, Canadian construct-level market shares were compared with published data from two national registries that report implant-model-level utilization in a format comparable to the present analysis: the American Joint Replacement Registry (AJRR, 2012-2024, voluntary submission, does not collect coverage data [7]) and the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR, 1999-2024, national, voluntary submission, complete coverage [3]). These comparisons were restricted to relative construct rank and market share

within fixation group (cemented vs. cementless) and were interpreted qualitatively rather than statistically, given substantial differences in reporting period: AJRR and, in particular, AOANJRR figures reflect cumulative multi-year registry cohorts, whereas the Canadian analysis reflects a 5-year incident cohort. Three additional registries including the Dutch Arthroplasty Register (LROI, national, mandatory submission, complete coverage), and the Swedish Arthroplasty Register (SAR, national, voluntary submission, complete coverage), do not report implant-model-level market share in a directly comparable format and were used only to provide general context on market concentration (i.e., the number of implant systems accounting for the majority of procedures), not for quantitative comparison.

5.4 Results

5.4.1 Study Population

The final study population included 219,386 TKA procedure records, with the majority of records from female patients (Table 5.1). Over the study period, annual procedure volumes fluctuated but increased overall from 2019 to 2023. A notable decrease in procedure volume occurred from 2019 to 2020, aligning with the start of the COVID-19 pandemic, and did not recover to 2019 levels until 2022 (Table 5.2). Case volume also varied substantially by province, with Ontario comprising the majority of cases over the study period, and the Northwest Territories reporting very few cases (Table 5.3).

Table 5.1: Cohort summary.

Total TKA (n)	**Mean Age (SD)**	**Percent Female**
219,386	68.5 (8.7)	58.6

Table 5.2: Annual TKA volume distribution (2019-2023).

Fiscal Year	**TKA (n)**
2019	47,848
2020	34,907
2021	33,971
2022	48,196
2023	54,464

Table 5.3: Provincial TKA volume distribution

Province/Territory	**TKA (n)**
Alberta	23,815
British Columbia	45,013
Manitoba	11,832
Newfoundland & Labrador	4,791
Nova Scotia	9,299
Northwest Territories	149
Ontario	111,850
Saskatchewan	12,637

5.4.2 Market Share Analysis

Over the study period, the national TKA implant market was dominated by 2 main manufacturers: Zimmer and Stryker, which together accounted for the majority of cases annually, reaching a combined 87% market share in 2023 (Fig. 5.1). A Pearson's chi-squared tests of independence on the manufacturer-by-fiscal-year cross-tabulation indicated that manufacturer market share was not independent of fiscal year ($\chi^2 = 1210.6$, df $= 40$, $p < 0.001$),

indicating that the relative distribution of manufacturers differed from one fiscal year to the next, though the negligible effect size suggests these year-to-year shifts were modest in magnitude (Cramer's V = 0.037).

The Cochran-Armitage trend test showed significant changes in market share over time for several manufacturers. Zimmer's market share increased from 47.5% in 2019 to 51.9% in 2023 (+4.4%, $p < 0.001$). MicroPort Orthopedics declined substantially from 4.9% to 1.7% (−3.2%, $p < 0.001$). Smith & Nephew and Stryker both showed modest declines (8.7% to 8.0%, −0.7%, $p < 0.001$, and 35.2% to 34.5%, -0.7%, $p < 0.01$, respectively).

Linear regression of manufacturer market shares from 2019 to 2023 confirmed a significant annual increase for Zimmer (β = +1.1% per year, p = 0.03) and significant declines for MicroPort (β = -0.73, p = 0.02) and Smith & Nephew (β = -0.14, p = 0.03). All other manufacturers did not show significant linear trends of market share in the regression model.

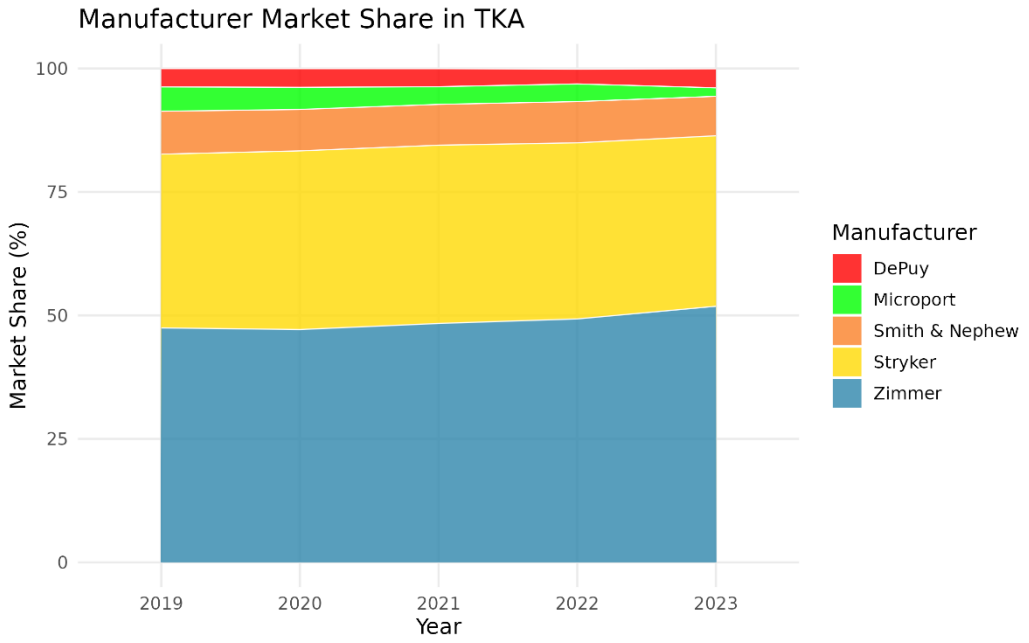


Figure 5.1: Manufacturer market share of TKA implants in Canada across fiscal years (2019-2023).

Manufacturer distribution also differed by province, with a large effect size (Cramer's V = 0.27; χ^2 = 63,133, df = 70, p < 0.001) (Fig. 5.2). In Manitoba, Smith & Nephew dominated the market; in Saskatchewan, Zimmer was the predominant manufacturer; in Alberta, Depuy held a larger share than in other provinces; and in British Columbia, MicroPort had relatively greater use (Fig. 5.2; Fig. 5.3). All pairwise provincial comparisons (with Bonferroni correction) showed significant differences in manufacturer distributions.

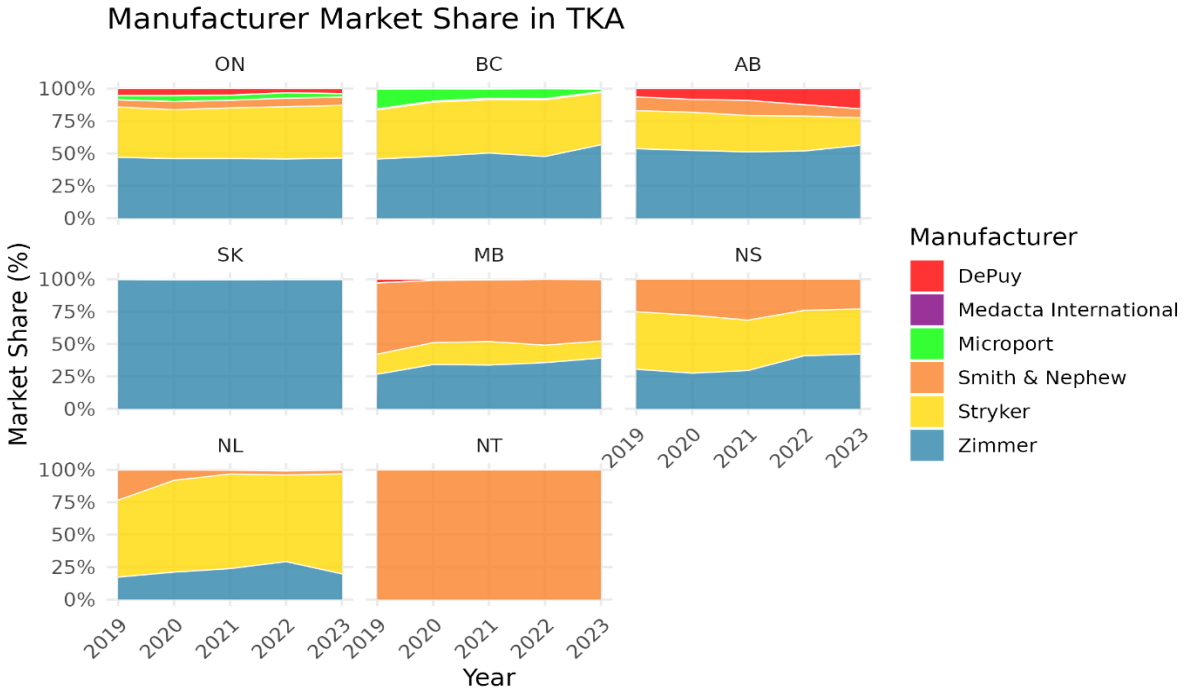


Figure 5.2: Provincial manufacturer distribution across fiscal years. ON = Ontario (n = 111,850), BC = British Columbia (n = 45,013), AB = Alberta (n = 23,815), SK = Saskatchewan (n = 12,637), MB = Manitoba (n = 11,832), NS = Nova Scotia (n = 9,299), NL = Newfoundland & Labrador (n = 4,791), NT = Northwest Territories (n = 149).

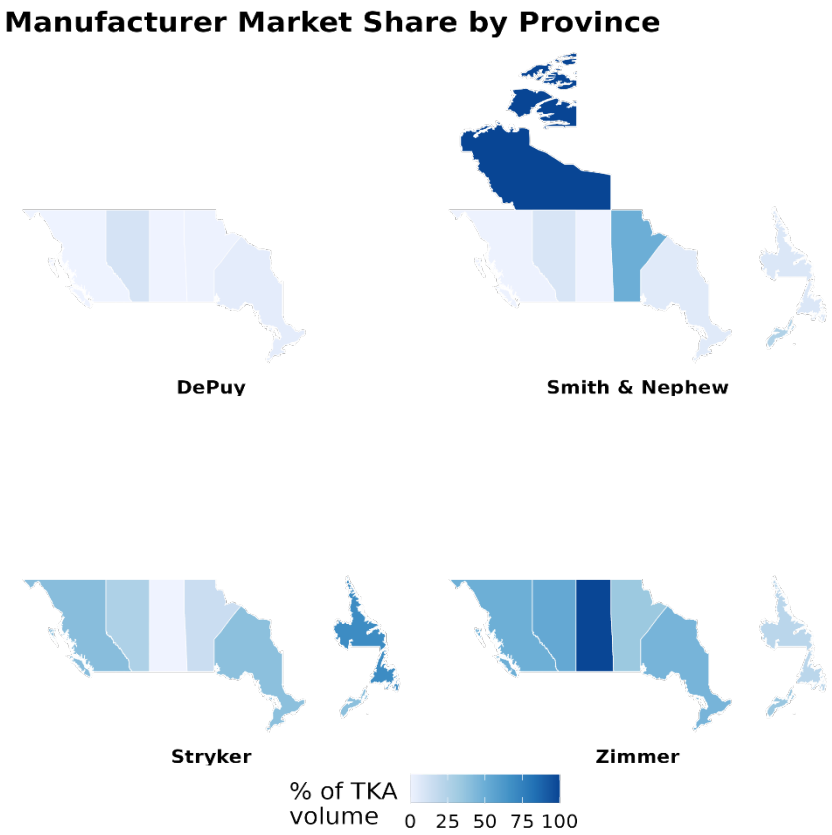


Figure 5.3: Provincial market share concentration by manufacturer (2019-2023).

5.4.3 Market Concentration

While starting at a high level in 2019 (HHI = 3,604), the Canadian TKA implant market increased in concentration to 3,962 in 2023 (Fig. 5.4), with HHI increases becoming increasingly steep between 2019 and 2020 and between 2022 and 2023.

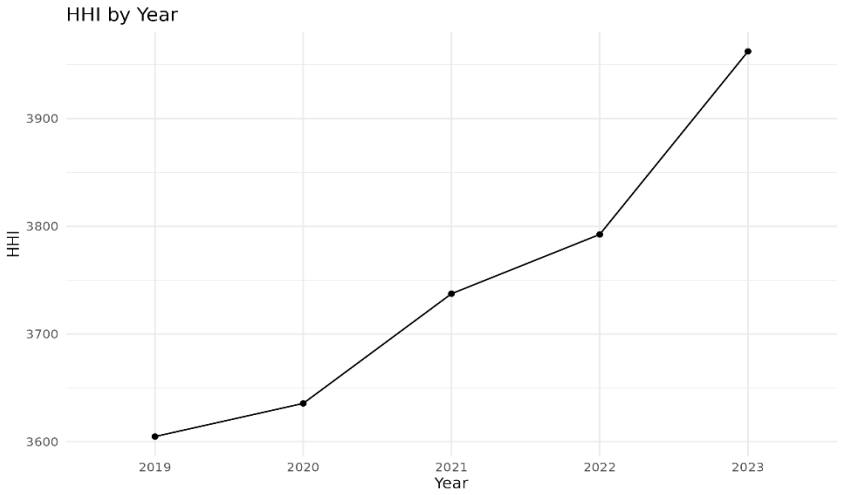


Figure 5.4: National HHI across fiscal years (2019-2023).

The provincial variation in manufacturer distribution is similarly reflected in provincial HHI trends (Fig. 5.5). While all provincial markets are highly concentrated (HHI>1,800), provinces such as Saskatchewan and the Northwest Territories (note that less than 150 TKAs were completed in NT during the study period) show near-complete concentration (HHI approximately 10,000), with only 1 primary manufacturer in the implant market. Most provinces maintained a steady market concentration with HHI values ranging from approximately 3,500 to 4,000. However, provinces such as British Columbia showed a steady increase in HHI over the study period, whereas others like Newfoundland and Labrador had greater variability (Fig. 5.5).

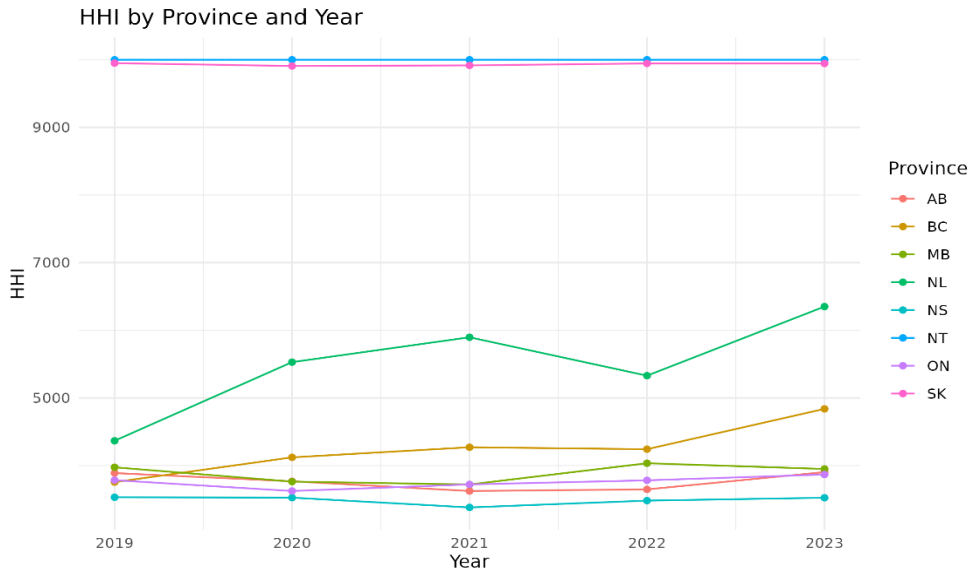


Figure 5.5: HHI by province across fiscal years. AB = Alberta, BC = British Columbia, MB = Manitoba, NL = Newfoundland & Labrador, NS = Nova Scotia, NT = Northwest Territories, ON = Ontario, SK = Saskatchewan.

5.4.4 Model Trends

Cochran-Armitage proportions trend tests of model combinations showed significant variation in use over the study period for nearly all femoral-tibial constructs analyzed (Fig. 5.6, Table 5.4). The largest shift was within Zimmer's Persona system: the cemented Persona CR construct (Persona Cemented CR + Persona Cemented) increased in use by 19.8 percentage points, while the cemented Persona PS construct fell by 10 percentage points. Stryker's Triathlon showed a similar fixation-driven pattern rather than a uniform trend: the cementless Triathlon CR with PA + Triathlon Tritanium construct increased by 9.0 percentage points, while the cemented Triathlon CR + Triathlon Cemented and Triathlon PS + Triathlon Cemented constructs both declined by 4.4 percentage points and 5.1 percentage points, respectively.

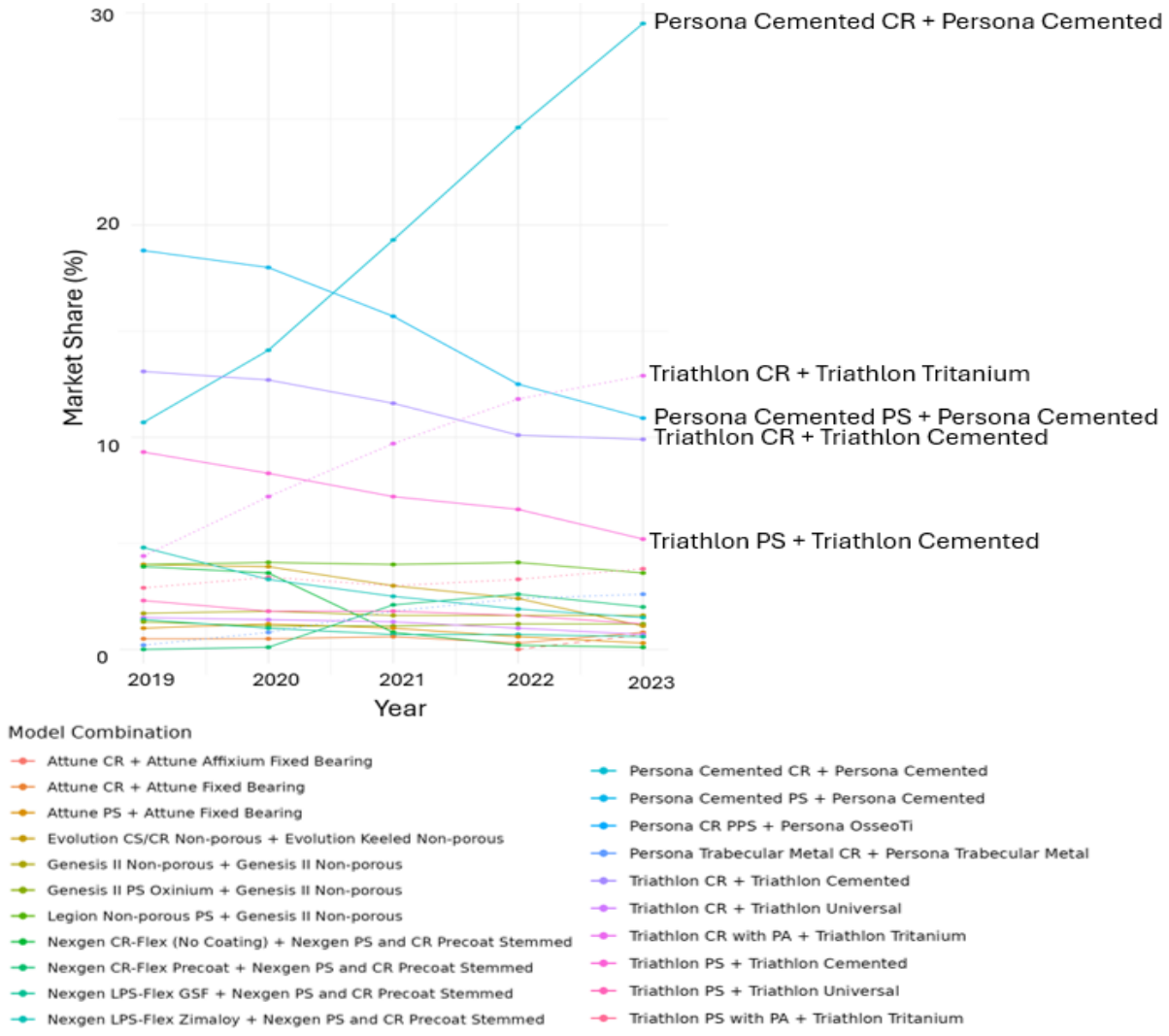


Figure 5.6: Model combination (femoral component + tibial component) market share across fiscal years (2019-2023) with fixation by line type.

Table 5.4: Cochran-Armitage proportions trend test results of model combination over fiscal years (2019-2023). Ordered from greatest to least absolute percentage change. Bolded model combinations indicate a statistically significant change in market share over the study period.

Model Combination	**Manufacturer**	$\boldsymbol{\chi^2_{\text{trend}}}$	*P*-value	**Effect Size**	**2019 Share (%)**	**2023 Share (%)**	**Change (%)**
Persona Cemented CR + Persona Cemented	Zimmer	6346.2	< 0.001	0.18	12.5	32.28	+19.8
Persona Cemented PS + Persona Cemented	Zimmer	2148.5	< 0.001	0.11	21.93	11.92	-10.01
Triathlon CR with PA + Triathlon Tritanium	Stryker	2376.3	< 0.001	0.11	5.12	14.1	+8.97
Triathlon PS + Triathlon Cemented	Stryker	887.7	< 0.001	0.067	10.83	5.72	-5.11
Nexgen CR-Flex (No Coating) + Nexgen PS and CR Precoat Stemmed	Zimmer	3739.7	< 0.001	0.14	4.56	0.07	-4.49
Triathlon CR + Triathlon Cemented	Stryker	528.3	< 0.001	0.052	15.22	10.85	-4.36
Nexgen LPS-Flex Zimaloy + Nexgen PS and CR Precoat Stemmed	Zimmer	1313.2	< 0.001	0.082	5.55	1.62	-3.93

Model Combination	Manufacturer	Chi-squared	P-value	Effect Size	2019 Share (%)	2023 Share (%)	Change (%)
Evolution CS/CR Non-porous + Evolution Keeled Non-porous	MicroPort	1073.6	< 0.001	0.074	4.66	1.24	-3.42
Persona Trabecular Metal CR + Persona Trabecular Metal	Zimmer	1077.7	< 0.001	0.074	0.27	2.79	+2.52
Nexgen CR-Flex Precoat + Nexgen PS and CR Precoat Stemmed	Zimmer	1267.2	< 0.001	0.081	0.02	2.18	+2.16
Triathlon PS + Triathlon Universal	Stryker	212.2	< 0.001	0.033	2.7	1.34	-1.36
Persona CR PPS + Persona OsseoTi	Zimmer	982.4	< 0.001	0.071	0	1.28	+1.28
Triathlon CR + Triathlon Universal	Stryker	215.2	< 0.001	0.033	1.73	0.75	-0.98
Nexgen LPS-Flex GSF + Nexgen PS and CR Precoat Stemmed	Zimmer	201	< 0.001	0.032	1.58	0.66	-0.92
Attune PS + Attune Fixed Bearing	DePuy Synthes	266.1	< 0.001	0.037	1.19	0.33	-0.85

Model Combination	Manufacturer	Chi-squared	*P*-value	Effect Size	2019 Share (%)	2023 Share (%)	Change (%)
Attune CR + Attune Affixium Fixed Bearing	DePuy Synthes	616.8	< 0.001	0.056	0	0.81	+0.81
Triathlon PS with PA + Triathlon Tritanium	Stryker	26.5	< 0.001	0.012	3.44	4.2	+0.77
Legion Non-porous PS + Genesis II Non-porous	Smith & Nephew	20.4	< 0.001	0.01	4.66	3.99	-0.67
Attune CR + Attune Fixed Bearing	DePuy Synthes	12.6	< 0.001	0.008	0.59	0.88	+0.29
Genesis II PS Oxinium + Genesis II Non-porous	Smith & Nephew	4.8	0.029	0.005	1.51	1.27	-0.24
Genesis II Non-porous + Genesis II Non-porous	Smith & Nephew	14.4	< 0.001	0.009	1.96	1.72	-0.23

Unlike the significant provincial variation observed at the manufacturer level, the femoral-tibial model combination distribution did not differ significantly across provinces ($\chi^2 = 38.4$, df = 105, p = 1, Cramer's V = 0.23), indicating that while the mix of manufacturers varies by province, the specific constructs used within each manufacturer's portfolio are broadly consistent nationally.

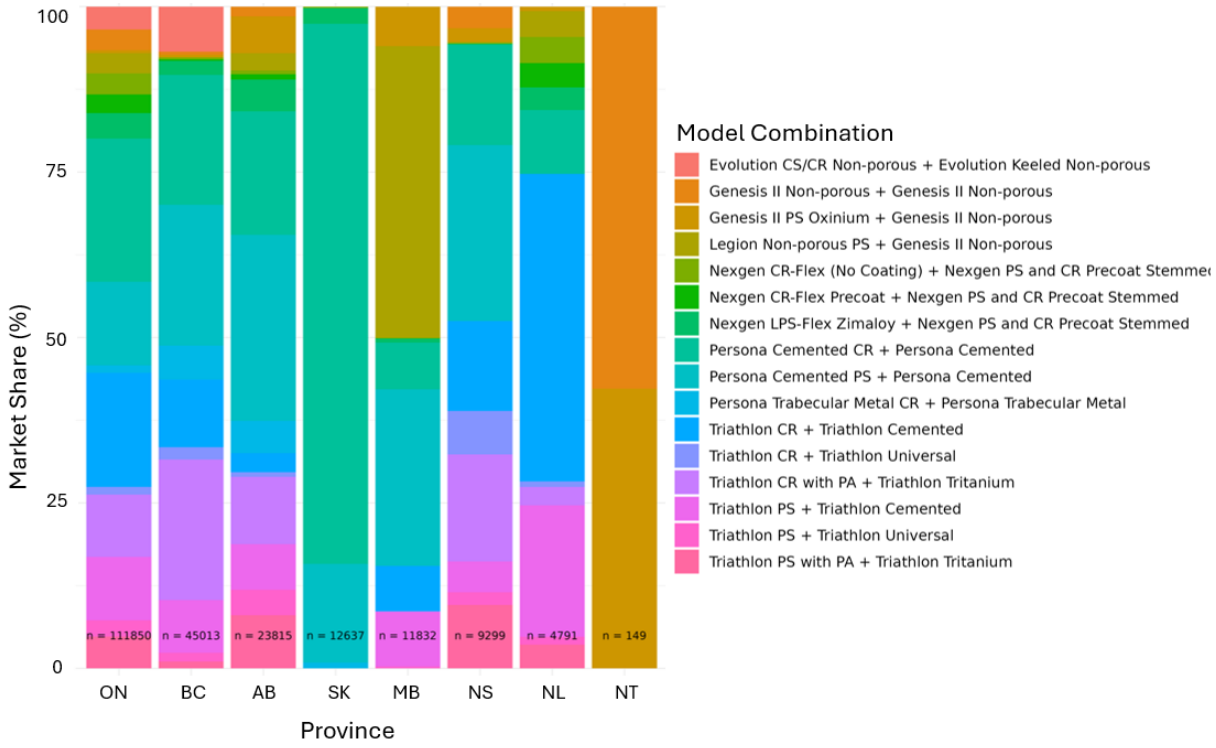


Figure 5.7: Model distribution across provinces (2019-2023). ON = Ontario (n = 111,850), BC = British Columbia (n = 45,013), AB = Alberta (n = 23,815), SK = Saskatchewan (n = 12,637), MB = Manitoba (n = 11,832), NS = Nova Scotia (n = 9,299), NL = Newfoundland & Labrador (n = 4,791), NT = Northwest Territories (n = 149).

Fixation & Stability

Disaggregation by tibial component fixation method (cemented (n = 183,723) versus cementless (n = 35,663)) showed market-share trends that differed from the model-level trends shown in Fig. 5.1 and Fig. 5.6. Similar to Fig. 5.1, Zimmer comprised the majority market share in the cemented market, with Stryker as the second largest (Fig. 5.7). However, in the cementless market, Stryker held over 75% of the market share, with other manufacturers reporting much smaller shares. Zimmer, however, showed a recent increase in its cementless market share to about 12%, though this remained a small share relative to Stryker.

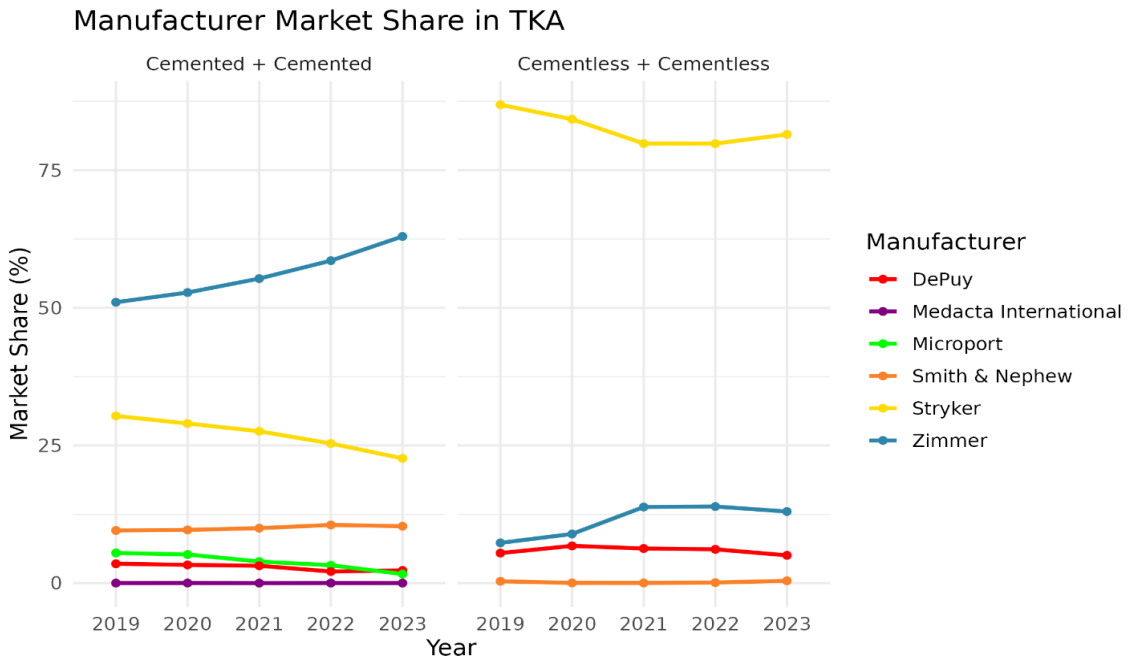


Figure 5.8: Manufacturer market share by fixation for femoral component + tibial component (2019-2023).

In cemented TKAs, the predominant models were the Persona CR Cemented + Persona Cemented (Zimmer), which showed an increased market share over the study period and the Persona PS Cemented + Persona Cemented (Zimmer), which decreased over the study

period (Fig. 5.6, Fig. 5.8). The third-largest market share was held by the Triathlon CR + Triathlon Cemented model (Stryker), which showed a slight decline over time (Fig. 5.8).

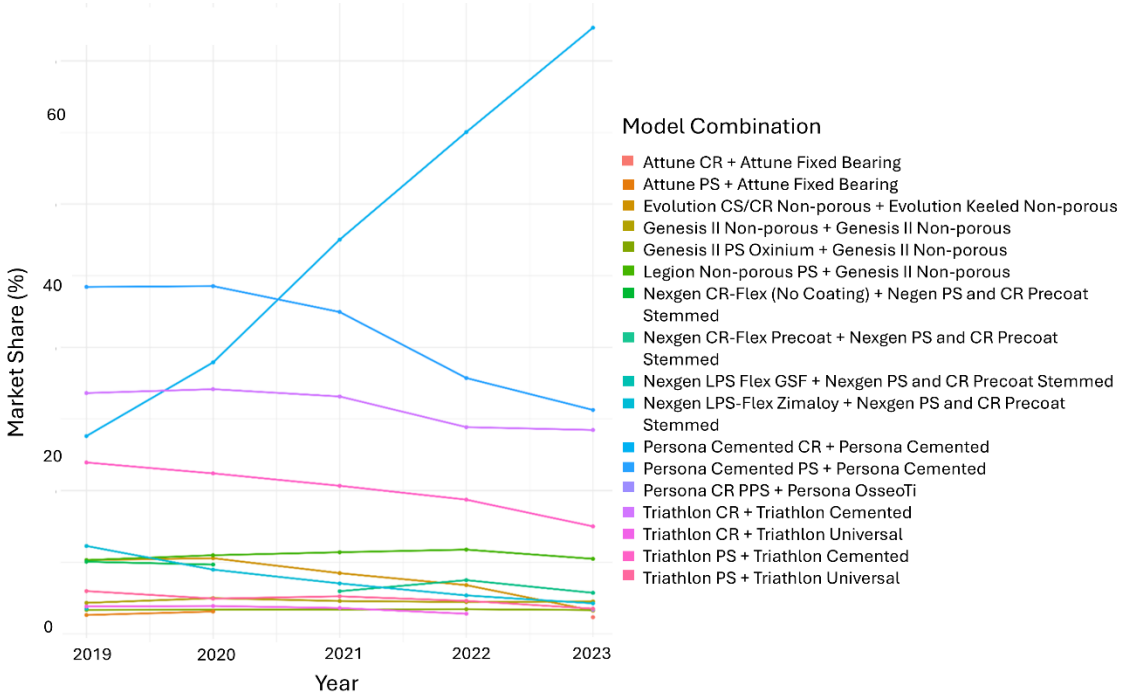


Figure 5.9: Cemented TKA model market share (2019-2023).

Unlike the cemented market, which had many different models, the cementless market had only 3 significant players. The Triathlon CR with PA + Triathlon Tritanium system (Stryker) dominated, with a market share of approximately 65% across fiscal years. In contrast, the posterior-stabilized version of this model (Triathlon PS with PA + Triathlon Tritanium) decreased over the study period, though it retained a greater market share than the Persona Trabecular Metal CR + Persona Trabecular Metal model (Zimmer), which accounted for less than 15% of the cementless market throughout the study period (Fig. 5.9).

As shown in Fig. 5.10, the overall model-level trends reported in Fig. 5.6 can be composed of distinct trends across insert stability subgroups. While most CR femoral systems were used with CR inserts, a substantial proportion also used medial pivot or anterior sta-

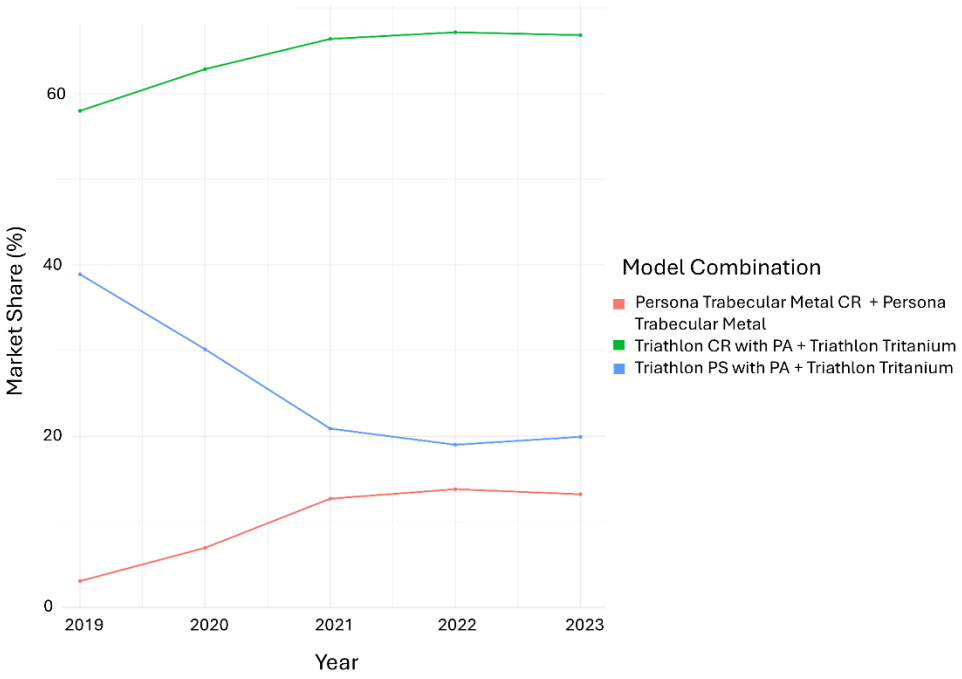


Figure 5.10: Cementless TKA model market share (2019-2023).

bilized designs. For example, the increase in Persona Cemented CR + Persona Cemented (Zimmer) was driven by both increased CR and MP insert use. In contrast, the overall decrease in Triathlon CR + Triathlon Cemented (Stryker) shown in Fig. 5.6 reflected a sharp decline in CR insert use that outweighed a moderate increase in AS insert utilization. Similarly, the cementless Triathlon CR with PA + Triathlon Tritanium system (Stryker) showed a decline in CR insert use and an increase in AS insert use, despite an overall increasing cumulative trend (Fig. 5.6).

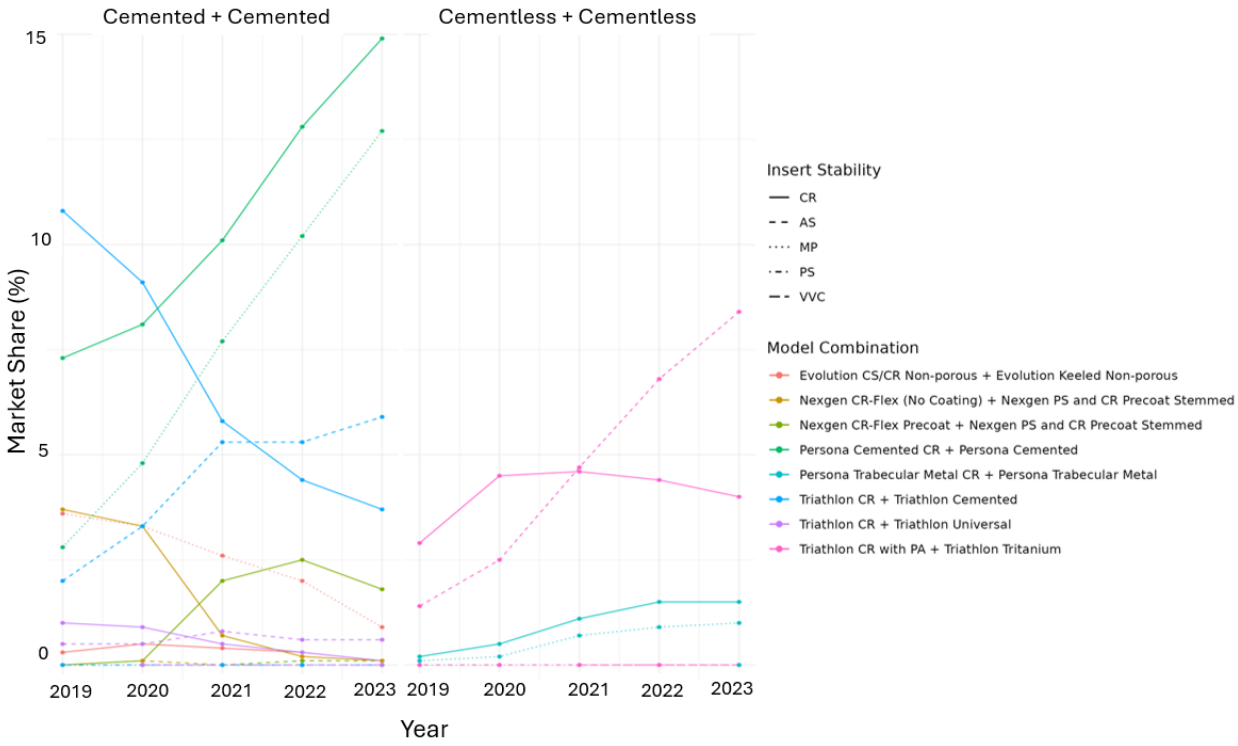


Figure 5.11: CR femoral systems market share across fiscal years (2019-2023), faceted by fixation. Line type indicates insert component stability. CR = cruciate retaining, AS = anterior stabilized, MP = medial pivot, PS = posterior stabilized, VVC = varus/valgus constrained.

5.4.5 Global Comparison

Across the CJRR, the AJRR (USA), and the AOANJRR (Australia), Triathlon CR (Stryker) was the dominant cementless construct despite their differing reporting periods (Table 5.5). For cemented TKAs, the two comparator registries diverged: AJRR shares were split more evenly across Persona and Triathlon CR/PS constructs, whereas AOANJRR showed greater Triathlon CR use. Canada's cemented market distribution was led by Persona CR and Persona PS, with Triathlon CR and Triathlon PS further behind (Table 5.5), which more closely resembles the AJRR pattern of broader distribution across both manufacturers' constructs than the AOANJRR pattern of Triathlon CR dominance.

Beyond the fixation-stratified comparison above, other national registries similarly describe a small number of implant systems accounting for the majority of procedures. The Swedish arthroplasty registry and the Dutch LROI both reported that the leading few femoral-tibial constructs accounted for the majority of the recorded primary TKA procedures in their respective cumulative surveillance cohorts, consistent with the market concentration pattern observed in the Canadian data. In the LROI, the top cementless model (DePuy, LCS) accounted for over 46% of cases [23], reflecting the single-model dominance in the Canadian cementless market. Similarly, in the Swedish registry, the most common TKA model overall (Zimmer, NexGen MBT) accounted for 45% of implants [24].

Table 5.5: Cemented vs. cementless construct concentration: Canada vs. AJRR and AOANJRR.Ordered by CJRR share within each fixation method.

Construct (fixation, CR/PS)	**CJRR (2019-2023)**	**AOANJRR (1999-2024)**	**AJRR (2012-2024)**
Cemented	n = 179,383	n = 474,828	n = 797,686
Persona CR + Persona	24.81%	8.71%	13.48%
Persona PS + Persona	18.18%	1.42%	11.12%
Triathlon CR + Triathlon	13.88%	18.79%	14.37%

Construct (fixation, CR/PS)	**CJRR (2019-2023)**	**AOANJRR (1999-2024)**	**AJRR (2012-2024)**
Triathlon PS + Triathlon	8.82%	2.42%	9.56%
Cementless	n = 34,172	n = 107,677	n = 91,065
Triathlon CR + Triathlon	60.25%	53.52%	77.84%
Triathlon PS + Triathlon	21.5%	1.49%	12.35%
Persona + Persona (CA/OsseoTi)	10.46%	10.57%	2.92%

Abbreviations: CJRR = Canadian Joint Replacement Registry, AOANJRR = Australian Orthopaedic Association National Joint Replacement Registry, AJRR = American Joint Replacement Registry, CR = cruciate retaining, PS = posterior stabilized.

5.4.6 Sex Analyses

Analysis of implant system distributions (at the model family level) by patient sex showed statistically significant variation ($\chi^2 = 78.9$, $p < 0.001$, Cramer's V = 0.019). Despite the statistical significance, the absolute differences in the proportion of implants used for male patients were small. For example, after Bonferroin adjustment for the system-versus-overall comparisons, the proportion of male patients was greater for Evolution + Evolution (43.2% vs. 41.4% overall; adjusted p = 0.022) and lower for Legion + Genesis (39.5%; adjusted p = 0.001) and Journey + Journey (37.1%; adjusted $p < 0.001$). Persona + Persona (41.9%) and NexGen + NexGen (40.4%) differed only before adjustment (unadjusted p = 0.012 and 0.013, respectively), and the remaining major systems (Triathlon + Triathlon, Attune + Attune, and Genesis + Genesis) did not differ significantly from the overall sex distribution.

5.5 Discussion

This study analyzed 219,386 TKA procedure records to examine implant market trends in Canada from 2019 to 2023. The Canadian market was highly concentrated at both the manufacturer and implant-model levels, with Zimmer and Stryker accounting for the largest shares, and notable manufacturer and model variation across provinces and fixation methods.

Market concentration increased nationally, with the HHI rising from 3,632 in 2019 to 4,059 in 2023. Even in 2019, the HHI was well above commonly cited thresholds for a highly concentrated market in competition policy literature [22]. The increase appears to have been driven primarily by the increasing share of Zimmer and declining share of MicroPort. At the model level, market trends closely mirrored this manufacturer-level consolidation. Zimmer's Persona and Stryker's Triathlon accounted for the majority of constructs nationally, while legacy systems such as NexGen and Genesis declined. The simultaneous decline of older models and rise of newer models within the same manufacturer may suggest that newer systems, such as Persona, are replacing legacy systems, such as NexGen, as the manufacturer's primary TKA platform rather than representing independent changes in demand.

Stratification by fixation method revealed a notable divergence in market concentration. While cemented TKAs broadly followed the national distribution, the cementless market was substantially more concentrated, with Stryker Triathlon CR/PS + Tritanium models accounting for the majority of cases across fiscal years. This suggests that adoption of cementless technology may be occurring within a more limited competitive landscape. Given that cementless TKA adoption has only recently gained popularity in Canada (Chapter 3), this pattern may reflect early adoption dynamics in which a limited number of manufacturers established market positions before competing systems expanded their offerings.

The greater concentration of cementless constructs may also reflect technological or regulatory barriers to entry. Regulatory requirements and approval processes may differ between markets, potentially limiting the range of cementless systems available in Canada compared to other countries. Many cementless systems rely on novel, proprietary porous-

ingrowth technologies that require regulatory approval before market release, and fewer constructs may have accumulated enough registry follow-up to establish a long-term performance record. Surgeons and institutions may therefore be more likely to adopt a limited number of cementless systems with established track records [29]. This interpretation remains speculative, however, and the present data cannot determine whether technological maturity, regulatory processes, robotics, procurement practices, or surgeon preference was primarily responsible for the observed concentration.

One potential explanation for market consolidation is differential implant performance. However, performance alone appears insufficient to explain the observed changes in market share. Although Zimmer's Persona has been reported to meet AOANJRR superiority benchmarks, indicating high performance, several manufacturers whose market shares did not increase over the study period have also demonstrated favourable performance, including Stryker's Triathlon, DePuy's Attune, and MicroPort's Evolution [3]. Thus, the observed pattern is not consistent with a purely performance-driven shift in market share and suggests that factors beyond clinical performance likely contributed to the market concentration observed in Canada.

Whether model consolidation itself confers a performance advantage remains uncertain. Robertsson et al. found that Sweden had lower revision rates than Denmark and Norway even when comparing only the three implant brands common to all three countries, suggesting that factors beyond implant selection contribute to outcome differences [30,31]. One possible mechanism is that a narrower implant repertoire allows surgeons to develop greater familiarity with fewer systems, which the literature has suggested may be associated with improved outcomes [32,33,39]. However, standardized surgical technique, surgeon case volume, and rehabilitation pathways remain plausible alternative explanations.

The pattern observed in Canada of consolidation toward a small number of implant systems, especially among cementless models, has also been described elsewhere. The American and Australian registries reported comparable patterns despite differences in reporting period; both suggest that a similarly narrow range of implant designs dominates utilization in each country. Other national registries such as the Dutch and Swedish also report substantial model concentration. The consistency of implant concentration across

registries with markedly different healthcare and procurement systems and reimbursement structures suggests that market concentration is not solely attributable to national healthcare or procurement policy. Given a small number of multinational manufacturers supply most major markets, national procurement systems select from a relatively common pool of products. Registry outlier reporting and the accumulation of comparative outcome data may also contribute to the continued use of a limited number of established designs [29].

This convergence, however, appears to occur mainly at the manufacturer level rather than the level of surgical philosophy. A comparison of AJRR with international registries showed that the US differs substantially from Australia, New Zealand, the UK, Norway, and Sweden in fixation method and prosthesis design preference despite similar patterns of brand dominance, indicating that market concentration and surgical philosophies are separable phenomena [34].

Beyond implant performance, institutional procurement structures likely play a substantial role in shaping national and provincial market dynamics. In Canada, implant purchasing is decentralized to the hospital or provincial health authority level and often facilitated through group purchasing organizations, which negotiate contracts based on pricing, volume commitments, and supplier evaluations [10,12]. All leading TKA manufacturers identified in this study (Zimmer, Stryker, DePuy, Smith & Nephew) are large multinational device companies, so company size alone is unlikely to explain Zimmer's disproportionate and growing share. More plausible contributors include contract incumbency, breadth of product catalogue, and bundled negotiation. Hip and knee arthroplasty implants are frequently negotiated together within a single vendor contract; thus, a manufacturer with a strong hip arthroplasty portfolio may gain an advantage in TKA contracting independent of TKA-specific performance or pricing [35].

Concentrating purchasing with fewer systems may also be a deliberate institutional strategy. Maintaining surgical instrumentation, trays, and staff training across multiple competing TKA systems carries a substantial overhead burden, creating an incentive for hospitals to standardize on one or two systems [25–27]. Academic and teaching hospitals may partially offset this consolidation through research-related implant carveouts that permit the use of models outside standard procurement agreements [36]. This dynamic may

also explain the near-single-supplier markets observed in low-volume provinces such as the Northwest Territories and Newfoundland and Labrador, where limited purchasing power and overhead burdens may preclude maintaining contracts with multiple manufacturers. Conversely, the greater model diversity observed in higher-volume provinces, and notably in Nova Scotia despite its relatively modest volume, suggests that procurement frameworks and local institutional policies also modulate these effects independently of volume alone.

Surgeon preferences may represent another important mechanism. Although surgeon-level data were unavailable, prior literature suggests orthopedic surgeons often prefer specific implant manufacturers and models based on their training and experience, influencing hospital purchasing decisions [16,37,38]. In provinces with fewer surgeons or institutions, these individual preferences may have a greater influence on the overall provincial market, resulting in lower implant diversity. These provincial trends may also persist as new surgeons adopt their supervising surgeons' preferences during training and maintain them throughout their careers [37]. Implant utilization may therefore reflect surgeon familiarity as much as patient-specific factors, and limited model diversity could restrict opportunities for patient-specific implant selection.

Statistically significant differences in model use by patient sex were observed, but the absolute differences were small. Given the large sample size, small proportional differences are expected to reach statistical significance. These findings should therefore be interpreted primarily as descriptive rather than as evidence of clinically meaningful sex-based differences in implant selection.

This study benefited from a large, national dataset and included manufacturer and model-level granularity not previously reported in Canadian registry reports. However, several limitations exist. The study period, 2019 to 2023, was only 5 years and overlapped with the COVID-19 pandemic. Thus, the drop in TKA volume from 2020 to 2021 likely reflects reduced elective procedures during the pandemic and may affect the linearity assumption of the Cochran-Armitage tests used. Provincial TKA volume distribution was non-uniform, with Ontario accounting for over half of the national volume (Table 5.3). However, a sensitivity analysis excluding Ontario yielded the same overall findings (Section E.4), suggesting that the national results were not driven solely by Ontario. More-

over, this dataset did not include surgeon or hospital identifiers, limiting detail to the entire province rather than the individual units responsible for procurement. It also did not include implant pricing information or procurement contract data that may inform market trends. Moreover, while HHI is a common market concentration analysis tool, it does not capture barriers to market entry or counterfactual competition; thus, it should be interpreted cautiously. Similarly, no clinical outcome data were available, limiting the ability to interpret market share trends in relation to implant performance.

Importantly, this study was not designed to formally evaluate the relationship between market concentration and clinical outcomes; rather, it serves as a descriptive foundation for future research examining whether consolidation toward fewer implant systems has measurable effects on patient care. In particular, outcome-focused analyses linking implant utilization patterns to revision rates or functional outcomes are an important next step.

In addition, future research should examine surgeon- and hospital-level implant model use to provide greater granularity on the factors influencing market trends. Given that implant procurement is decentralized at the hospital or health authority level, an investigation into hospital purchasing practices, such as specific group purchasing agreements, would improve procurement transparency and perhaps shed light on why certain markets are dominated by so few manufacturers.

5.5.1 Conclusion

The Canadian TKA implant market was highly concentrated from 2019-2023, with substantial provincial variation and near-single-supplier markets in some regions. This degree of concentration was broadly consistent with the pattern described in the comparator registries (AJRR, AOANJRR, Table 5.5), where a small number of large multinational suppliers similarly account for the majority of recorded procedures, suggesting that limited-supplier dynamics are not unique to Canada, although surgical preferences and fixation practices remain distinct across countries. The observed patterns are likely influenced by a combination of procurement structures, institutional standardization, and surgeon familiarity, but the relative contribution of these factors and their implications for clinical

outcomes remain uncertain. As TKA volumes continue to increase, monitoring implant market concentration and understanding the institutional factors that shape implant selection will be important for ensuring that procurement practices remain aligned with patient care and clinical outcomes.

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Chapter 6

Clustering

6.1 Abstract

6.1.1 Background

Total knee arthroplasty (TKA) implant selection is a consequential clinical decision; however, prescribing patterns are rarely studied as a distinct outcome. It remains unclear whether observed variation in complete implant configurations reflects manufacturer/model identity, functional design, or patient characteristics. This study aimed to identify recurring configurations of femoral, tibial, insert, and patellar components and assess their associations with model identity, functional design, and patient demographics.

6.1.2 Methods

Procedure-level, primary TKA implant data from the Canadian Joint Replacement Registry (2019-2024, n = 177,190) were clustered using Factor Analysis of Mixed Data (FAMD) followed by k-means clustering with two input-variable sets: one including implant model name (Question A) and one excluding model name but including femoral and tibial AP/ML

ratios as implant-design proxies (Question B). Clustering was cross-validated using Gower-distance silhouette and bootstrap Jaccard stability. Solutions were compared using adjusted Rand index and Cramér's V. Multinomial logistic regression assessed associations with age, sex, province, and fiscal year. Question B was repeated in sex-disaggregated cohorts.

6.1.3 Results

Both Question A and B analyses converged on six-cluster solutions with moderate validity and stability (silhouette 0.44-0.53; Jaccard 0.64-0.69). Question A clusters were concentrated in three model-dominated groups (92% of procedures), while Question B, despite excluding model information, identified six functional configurations. The solutions were strongly associated but only had moderate raw agreement (Cramér's $V = 0.712$; adjusted Rand index $= 0.524$), indicating that brand and design were related but not interchangeable. Age and sex were statistically significant but weak predictors (Cramér's $V \leq 0.08$), whereas province and fiscal year showed stronger associations. Sex-stratified analyses found fixation method strongly organized implant configuration clusters among the male cohort (Cramér's $V = 0.95$) but not the female cohort, for which patellar resurfacing and stability type were more associated with cluster membership.

6.1.4 Conclusion

TKA implant selection in the CJRR followed recurring configuration patterns shaped more by manufacturer, functional design, provincial context, and time than by patient characteristics. The persistence of similar configurations after removing model information indicated that implant design captured meaningful variation beyond model name, while their strong association with implant model also suggests that manufacturer product lines may limit compatible configuration options. These findings support assessing TKA implant use and outcomes based on complete system configurations rather than individual implant traits in

isolation and highlight the importance of sex-stratified analyses when examining differences in implant selection.

6.2 Introduction

Total knee arthroplasty (TKA) is among the most common elective procedures performed in Canada [1]. Volumes have grown steadily over the past two decades, with the exception of a decline during the COVID-19 pandemic [1]. Volumes subsequently recovered and have exceeded pre-pandemic levels since 2022 [1]. Each TKA procedure requires the selection of femoral, tibial baseplate, tibial insert, and optionally patellar implant components that may differ in fixation method, articular geometry, constraint level, bearing mobility, and material composition. This choice may have clinical consequences, as component design has been associated with functional outcomes and revision risk; as well as economic consequences, given differences in implant system procurement costs [2–4]. Despite the significance of these selections, comparatively little research has examined implant selection itself as a primary outcome, rather than as an input to be adjusted for when studying downstream results such as pain, function, or revision.

Substantial variation exists in TKA across Canada (Chapters 3 to 5). Previous analyses of the Canadian Joint Replacement Registry (CJRR) documented substantial differences between provinces in age-adjusted TKA rates and in the use of specific implant categories, such as unicompartmental designs, that could not be explained by underlying differences in patient demographics or disease burden [5]. Surgeon-level surveys similarly suggest that implant selection is influenced by surgeon preference, training, and brand familiarity, alongside patient-specific clinical considerations [6,7]. North American surgeons report using fewer than two knee implant brands per year on average and identify anticipated improvements in outcomes and component cost, rather than patient characteristics, as the primary drivers of switching between implant systems [6]. More recent single-centre work has also linked implant selection to surgeon fellowship training, years in practice, and the adoption of robotic-assisted techniques, reinforcing that prescribing behaviour is

not uniform across the specialty and is only partly explained by clinical indication [7]. This literature indicates that implant selection represents an important source of practice variation. However, existing studies have typically examined individual implant attributes or single institutions in isolation, rather than considering the multidimensional interplay among manufacturer, implant design, and patient characteristics.

Variation in prescribing practices may also reflect disparities in equitable access to treatment, underscoring the broader implications of this practice variation. Registry-based work has shown that women and men experience different rates of TKA utilization and different revision risk profiles [5], and that race, ethnicity, and sex are associated with differences in TKA access and outcomes more broadly [8]. Socioeconomic status has also been linked to lower rates of joint replacement for osteoarthritis, suggesting that structural factors, and not only clinical need, shape who receives care [9]. If implant selection itself varies systematically by patient demographics, independent of surgical indication (i.e. not whether a patient receives surgery, but what type of implant configuration they are given when they do), this would constitute a distinct and previously under-examined dimension of potential inequity in TKA care.

Most existing literature on clustering and phenotyping work in healthcare has focused on comorbidity structure, disease trajectories, or outcome trajectories rather than on device-level prescribing behaviour [10,11]. Unsupervised methods such as clustering have been successfully applied to electronic health record and registry data to identify clinically coherent subgroups from both mixed categorical and continuous variables [12–15]. However, these approaches have rarely been applied to implant component data. Consequently, the literature can describe variation in rates and outcomes but provides limited insight into the underlying structure of prescribing, specifically, whether TKA implant selection can be characterized by a small number of interpretable prescribing configurations or archetypes, whether these configurations are driven more by manufacturer identity or functional design, and whether patient demographics are associated with the configuration a patient receives.

The present study addressed this gap using component-level implant data from the CJRR, linked to patient and procedure-level records. Two related but distinct cluster-

ing analyses were conducted. The first, Question A, aimed to identify clusters of TKA procedures based on implant model identity (model name), categorical design features (fixation, stability, mobility, and material), and system-level indicators (patella and stem use). This analysis addressed the questions of prescribing patterns and equity by examining whether distinct implant "archetypes" exist and whether patient age, sex, province, and year are associated with membership in these archetypes. The secondary analysis (Question B) excluded model name and clustered procedures solely according to functional configuration. This assessed whether similar implant archetypes emerged across different manufacturers rather than simply reflecting brand identity. If the clusters identified in Question A largely corresponded to individual implant models, this would suggest that functional design features contribute little additional differentiation beyond manufacturer/model identity. Cross-tabulating the Question A and Question B solutions aimed to separate brand-driven variation from design-driven variation explicitly, rather than conflating the two within a single model, and represented a validity check that, to our knowledge, has not been applied to implant registry data of this kind.

6.3 Methods

6.3.1 Study Design and Data Source

This retrospective cohort study used data from the Canadian Joint Replacement Registry (CJRR) for the fiscal years (May-April) 2019 to 2023, accessed through the Graduate Student Data Access Program of the Canadian Institute for Health Information (CIHI). CJRR implant data are drawn procedure records linked to the International Prosthesis Library (IPL) which provides manufacturer, model, and component-level attributes for each implant used [5].

Parts of this material were based on data and information provided by the Canadian Institute for Health Information. However, the analyses, conclusions, opinions, and statements expressed herein are those of the author and not necessarily those of the Canadian Institute for Health Information.

6.3.2 Study Population

Eligible records comprised primary total knee arthroplasty procedures, with or without patellar resurfacing, performed on patients aged 18 years or older. To ensure adequate registry coverage, the cohort was restricted to provinces with either mandatory CJRR submission (Manitoba, British Columbia, Ontario) or a minimum 70% submission rate (Newfoundland and Labrador, Nova Scotia, Saskatchewan, Alberta, Northwest Territories). CJRR implant data are captured at the component level, with each femoral, tibial, insert, patellar, and stem component recorded as a separate row; these records were reshaped to the procedure level (one row per joint replacement procedure, identified by a unique joint identifier) prior to analysis.

The initial CJRR 2019-2023 TKA dataset comprised 230,922 component-level records. After restricting to procedures with valid TKA constructs (femoral and tibial component present), reshaping to the procedure level, and removing rows with missing values across the union of clustering variable sets for Question A and Question B, 177,214 procedures met inclusion criteria (Section F.1). After rare levels were collapsed or removed due to too few counts, the final sample size for both Question A and B clustering analyses was 177,190 (Section F.1). This complete-case final cohort was used for both the Question A and Question B analyses to ensure that differences in clustering solutions reflect differences in variable sets rather than differences in sample composition.

6.3.3 Variables

Patient- and procedure-level variables retained for cohort description and post-clustering analysis included patient age at surgery, sex, fiscal year, submitting province or territory, and most responsible diagnosis. Most responsible diagnosis was retained for descriptive purposes but excluded from the clustering variable set itself, as more than 99% of cases in the cohort reflect a diagnosis of osteoarthritis and thus, the variable carried little discriminating information for clustering.

Implant-level candidate variables reshaped to the procedure level and assessed for clus-

tering included implant model name (recorded separately for femoral and tibial components), fixation method (cemented or cementless, recorded separately for femoral and tibial components), stability (e.g., cruciate-retaining, posterior-stabilized, determined by the recorded stability of the tibial insert, and if not available, the stability of the femoral component), mobility (fixed-bearing versus rotating- or mobile-bearing insert), polyethylene and metal material (recorded separately for the femoral, tibial, and tibial polyethylene insert components), femoral and tibial antero-posterior (AP) and mediolateral (ML) ratios, and insert thickness (continuous), and binary indicators for whether patellar resurfacing or a modular stem (recorded separately for femoral and tibial stem components) were used.

Administrative and identifier fields (joint identifier, data source, replacement type, and catalogue numbers) were excluded from all analyses, as were fields that were redundant with a retained variable or that applied uniformly across the cohort.

6.3.4 Data Preprocessing

Variable distributions were assessed prior to analyses. Patellar and stem component attributes are only recorded when those components were used; thus, patella and stem use were retained as explicit binary indicators. The categorical variables, particularly model name, which had dozens of distinct values, were processed with a rare-level collapsing function that grouped infrequent categories ($n < 20$) into an "other" level to avoid destabilizing distance- and likelihood-based clustering methods with high cardinality and sparsely populated categories. Candidate variables were screened for redundancy prior to clustering. Associations between categorical variables were evaluated using Cramér's V, while Pearson's correlation was used for pairs of continuous variables. TKA implant component configurations are subject to compatibility constraints and clinical convention, thus moderate associations among implant variables are expected and do not necessarily indicate redundancy. Therefore, redundancy thresholds of Cramér's $V > 0.7$ or Pearson's $r > 0.8$ were set deliberately high [16,17]. Where associations exceeded these thresholds, one variable from each pair was excluded to minimize overlapping information in the clustering analysis (Section F.2). An exploratory analysis to assess the relationship between model

name (used in Question A) and the dimensional variables (femoral and tibial AP/ML ratios, used in Question B) was conducted with an analysis of variance (ANOVA) test and reported with eta squared (η^2) effect size (Section F.3).

The 1.5 times the interquartile range (IQR) rule was used to identify outliers in numerical variables by classifying values below Q1 $-$ 1.5 $\times$ IQR or above Q3 $+$ 1.5 $\times$ IQR [18]. The identified outliers were subsequently excluded from the final dataset. The results of the outlier detection, rare-level collapse, and variable redundancy tests are reported in Section F.2. Continuous variables were also standardized to mean zero and unit standard deviation using the built-in scale function in R.

Prior to clustering, the Hopkins statistic and visual assessment of pairwise dissimilarity structure were used to confirm that the prepared data exhibited clustering tendency rather than approximating a random, unstructured distribution [19].

6.3.5 Clustering Strategy

Two clustering analyses were conducted on the same procedure-level cohort, differing only in the variable set supplied to the clustering algorithm (Table 6.1). In the primary analysis (Question A), procedures were clustered using the variable set listed in Table 6.1, including implant model identity (brand name) as well as fixation, stability, mobility, material, and system-level indicators (patella and stem use). This analysis aimed to address the central prescribing-pattern and equity question by exploring whether TKA procedures can be characterized by a small number of clinically interpretable prescribing configurations and whether patient- and system-level factors are associated with membership in these configurations. In the secondary, exploratory analysis (Question B), model identity (model name) was dropped and replaced with the femoral and tibial component AP/ML ratios, dimensional attributes serving as proxies for implant design. Clustering was repeated using the AP/ML ratio and the remaining functional configuration variables (Table 6.1). This analysis assessed whether similar functional implant configurations emerged across manufacturers, independent of brand identity, and provided a robustness and validity check

for Question A. The two solutions were compared directly to separate model-driven from design-driven variation.

Table 6.1: Clustering variables for Question A and Question B cluster analyses. See Section F.2 variable screening and inclusion results producing this final variable set.

Variable	**Question A**	**Question B**
Femoral Model Name	X	
Tibial fixation	X	X
Stability	X	X
Mobility	X	X
Femoral Metal Material	X	X
Tibial Metal Material	X	X
Insert Polyethylene Material	X	X
Femoral AP/ML Ratio		X
Tibial AP/ML Ratio		X
Has Patella?	X	X
Has Femoral Stem?	X	X
Has Tibial Stem?	X	X

6.3.6 Sex-Disaggregated Exploratory Analysis

The Question B clustering was also run on sex-disaggregated cohorts, following the same clustering method and number of clusters selection process as the full cohort analyses (outlined below). Rather than only investigating sex differences as a post-hoc comparison, within a pooled cluster structure, this analysis re-ran the full candidate-method comparison, number of clusters selection, and stability validation separately within female-only and male-only procedures, allowing the number and composition of clusters themselves to differ by sex if the underlying implant configurations used in female and male patients

differed. These clustering solutions were then compared by the number of clusters and cluster characteristics.

This additional analysis was restricted to Question B and not applied to Question A because the model name variable in Question A showed high cardinality, and some levels were already sparsely populated in the pooled sample. Thus, disaggregation would have required additional rare-level collapsing and risked small, unstable clusters. Focusing on Question B also prevented potential sex-linked differences in implant models, such as sex-specific models (e.g. Zimmer's Gender Solutions TKA), from confounding cluster structure.

6.3.7 Candidate Clustering Methods

The procedure-level dataset combined categorical (nominal) and continuous variables, so clustering methods capable of natively handling mixed-type data were prioritized over approaches that require forcing categorical variables into a Euclidean-distance framework via one-hot encoding [20,21]. For both Question A and Question B, four candidate clustering methods were run in parallel on a subset of the data (n = 10,000), to allow cross-method validation: K-Prototypes, a centroid-based method that extends k-means to mixed data by combining a Euclidean distance component for continuous variables with a simple matching distance component for categorical variables [22]; KAMILA (k-means for mixed large-scale data), a related partitional method designed for mixed-type data at scale [49]; Factor Analysis of Mixed Data (FAMD) followed by k-means on the resulting low-dimensional continuous embedding, an approach with precedent in large-scale clinical phenotyping [14,15]; and latent class analysis (LCA), a model-based, probabilistic approach well suited to categorical-dominant data that yields cluster membership probabilities rather than hard assignments [13,23]. Testing multiple algorithms, rather than relying on a single method, followed the recommendation of recent clustering methodology reviews that no single algorithm dominates across health applications and that consistency across methods strengthens confidence that identified structure is not an artifact of one method's assumptions [10,19,24]. Gower distance, which accommodates mixed nominal, ordinal, and continuous variables, was used to compute a common dissimilarity matrix

for cross-method silhouette comparison and for methods that require an explicit distance matrix [21,25].

The final clustering method was chosen primarily based on cluster stability (bootstrap Jaccard), followed by fit quality (Gower silhouette), and clinical interpretability of the clusters (Section F.4. The final clustering solution was determined and run separately for each of the Question A and Question B variable subsets (and sex-disaggregated cohorts).

6.3.8 Statistical Analysis

Once a final clustering solution was selected for Question A and for Question B, clusters were characterized descriptively using means and standard deviations for continuous variables and frequencies for categorical variables. Pearson's chi-squared tests of independence were used to compare categorical distributions across clusters, and analysis of variance (ANOVA) was used for continuous variable comparisons. In addition to P-values, effect sizes (Cramér's V, Cohen's d) were reported. No adjustment for multiple comparisons was applied to these tests; given the very large sample, most comparisons reached $p < 0.001$, and interpretation therefore focused on effect sizes. Effect sizes were interpreted according to established thresholds adjusted for table dimensions by dividing the conventional thresholds for a $2 \times k$ table (negligible < 0.10, small 0.10 to < 0.30, medium 0.30 to < 0.50, large ≥ 0.50) by $\sqrt{(\min(n_{\text{rows}}, n_{\text{columns}}) - 1)}$ [50].

To address the central equity question, cluster membership from the Question A solution was modelled using multinomial logistic regression as a function of patient age, sex, submitting province, and fiscal year, with the largest cluster serving as the reference in the model. These variables have been previously reported to be associated with implant selection [31–33], and preliminary findings in this thesis, support their inclusion (Chapters 3 to 5). This aimed to identify demographic, regional, and temporal predictors of prescribing-pattern membership. Model fit was assessed with McFadden pseudo-R^2 which compares the log-likelihood of the fitted model with that of an intercept-only model ($1 - \log(L_{\text{model}}) / \log(L_{\text{null}})$) [47], and the multiclass area under the receiver operating characteristic curve (AUROC), calculated using the Hand and Till generalization, which averages the pairwise

AUROCs across all pairs of outcome classes (0.5 = discrimination no better than chance; 1 = perfect discrimination) [48,50]. Confidence intervals for AUROC estimates were not computed; given the large sample sizes, sampling uncertainty in these estimates was expected to be small. The multinomial regression results were reported as odds ratios (OR) with 95% confidence intervals (CI).

The Question A and Question B cluster solutions were cross-tabulated to examine differences in cluster membership. To quantify the similarity between clustering solutions, the adjusted Rand index was used, which also corrects for the agreement that could occur by chance, and aimed to separate the portion of clustering structure attributable to manufacturer/model identity from the portion attributable to functional design configuration. All analyses were performed in R (v4.3.0) and used the clustMixType, kamila, FactoMineR/factoextra, poLCA, cluster, and fpc packages [27,29,34–37].

6.4 Results

6.4.1 Study Population

Of the 177,190 procedures included in the final clustering dataset, the majority were among female patients and occurred in Ontario (Table 6.2). The demographics of the sex-disaggregated cohorts were similar to that of the full, combined cohort.

Table 6.2: Cohort characteristics for each of the clustering datasets. Demographic variables included are those later examined post-clustering. Note: both Question A and B used the same cohort.

Clustering Cohort	**N**	**Mean age (SD)**	**% Female**	**% Ontario**
Question A	177,190	68.8 (8.6)	59.2	50.9
Question B	177,190	68.8 (8.6)	59.2	50.9

Clustering Cohort	N	Mean age (SD)	% Female	% Ontario
Question B Female	101,123	68.7 (8.7)	100	51.3
Question B Male	70,804	68.9 (8.4)	0	50.4

6.4.2 Pre-Clustering Analyses

The Hopkins statistic, computed on a subsample of 1,000 procedures, was 0.927, and thus indicated strong clustering tendency. A conservative sample-size heuristic requiring n $\geq$ 2^k for k clustering variables indicated that the final 10-variable sets (Table 6.1) were adequately sampled (2^10 = 1,024, Section F.2). Exploratory FAMD after redundancy-based variable reduction to the final variable sets used in each analysis, showed that the first five FAMD dimensions explained 36.5% of variance for Question A and 45.9% for Question B, and thus suggested reasonable clustering efficacy.

6.4.3 Question A: Primary Clustering Solution (Implant Model + Design Features)

Of the four clustering methods evaluated on the 10,000-procedure test sample, FAMD with k-means achieved the highest cross-method Gower-distance silhouette score (0.40, versus 0.33 for K-Prototypes, -0.02 for KAMILA, and 0.47 for LCA, the latter discounted for poor bootstrap stability; Section F.4) and was applied to the full analytic sample (n = 177,190). Across k = 2-10, silhouette width peaked at k = 6 (silhouette = 0.533 in FAMD-reduced space; 0.35 on a 10,000-row Gower-distance subsample used for cross-method comparison), with mean bootstrap Jaccard stability of 0.693. Cluster sizes and defining features are summarized in Table 6.3 and visualized in Section F.5; full cluster summaries are also available in Section F.5.

Table 6.3: Question A clustering features summary (n = 177,190).

Cluster	n (%)	Dominant model	Fixation	Stability	Other features
1	41,610 (23.5%)	Triathlon (99.9%)	Cementless (61.4%)	AS (66.4%)	No patella (73.8%)
2	51,321 (29.0%)	Triathlon (56.4%)	Cemented (99.0%)	PS (56.6%)	UHMWPE insert (81.0%)
3	89 (0.1%)	Other/mixed (58.4%)	Cemented (100%)	Hinged (68.5%)	Rotating mobility (79.8%)
4	12,802 (7.2%)	Legion (73.1%)	Cemented (99.9%)	PS (89.8%)	Patella resurfaced (64.7%)
5	1,595 (0.9%)	Attune (67.2%)	Cemented (51.0%)	CR (42.2%)	Rotating mobility (100%)
6	69,773 (39.4%)	Persona (100%)	Cemented (100%)	MP (49.7%)	Asymmetric tray; patella resurfaced (53.0%)

Abbreviations: AS = anterior-stabilized; PS = posterior-stabilized; CR = cruciate-retaining; MP = medial-pivot.

6.4.4 Question A: Cluster Characterization

As evident from Table 6.3 and Fig. 6.1, categorical implant design variables used in clustering, as expected, showed substantial between-cluster associations (Cramér's V: insert mobility = 1.00, tibial symmetry = 1.00, femoral model = 0.83, tibial fixation = 0.73, insert stability = 0.57). Continuous variables not used as direct clustering inputs also differed significantly by cluster (all ANOVA $p < 0.001$); tibial and femoral AP/ML ratio showed large effect sizes ($\eta^2 = 0.75$ and 0.67, respectively), while insert thickness showed a small-to-moderate effect ($\eta^2 = 0.085$). Among patient- and system-level variables not used

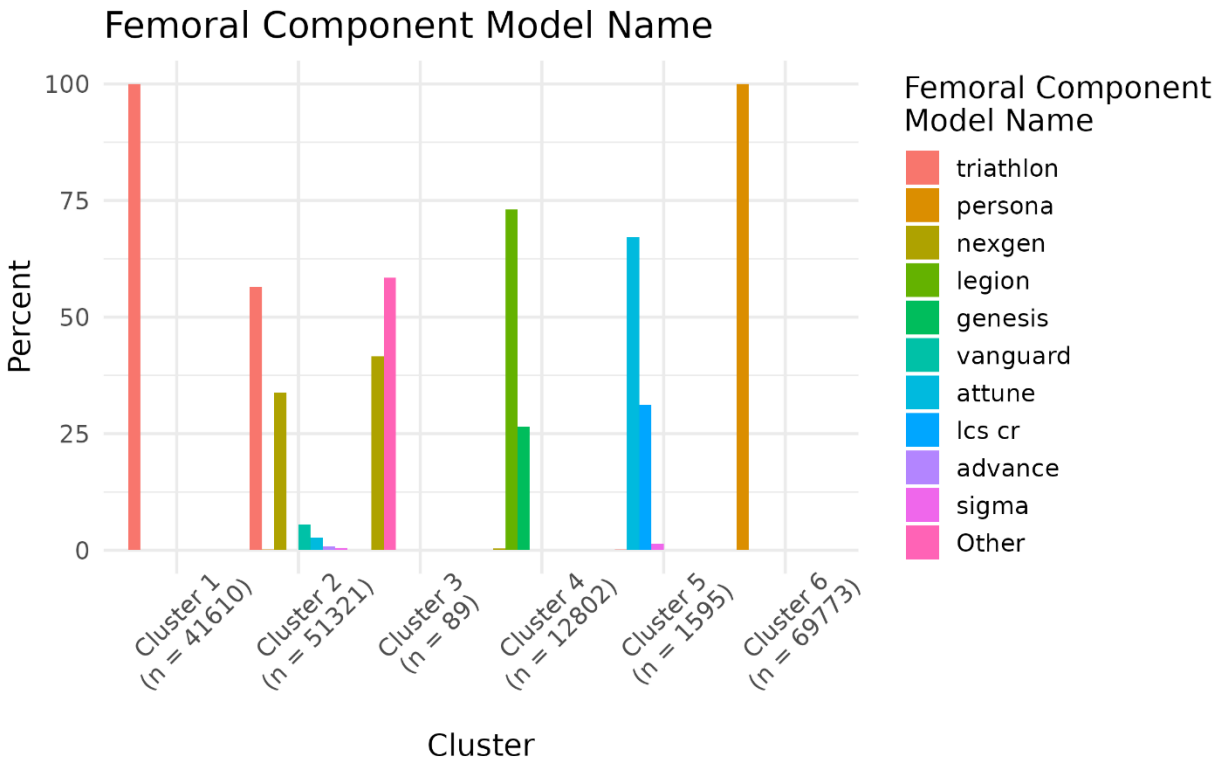


Figure 6.1: Question A clusters femoral model name distributions.

in clustering, submitting province showed a strong association with cluster membership (Cramér's V = 0.26), most responsible diagnosis a small association (V = 0.08), and sex a very small association (V = 0.03). Patient age differed significantly across clusters but also with a small effect size ($\eta^2 = 0.006$; cluster mean ages ranged from 67.8 to 69.5 years), and fiscal year showed a small-to-moderate effect ($\eta^2 = 0.038$). All other plots of variable distributions across clusters are located in Section F.5.

The multinomial logistic regression predicting cluster membership from age, sex, and fiscal year (reference: Cluster 6), showed that age and sex reached statistical significance in most cluster comparisons (e.g., male sex associated with odds ratios ranging from 0.53, 95% CI: 0.33-0.85 (Cluster 3) to OR = 1.32, 95% CI:1.20-1.46 (Cluster 5) relative to Cluster 6), but overall model fit was low (McFadden pseudo-$R^2 = 0.018$; multiclass AUROC = 0.575).

6.4.5 Question B: Primary Clustering Solution (Functional Configuration Only)

With implant model identity removed, FAMD with k-means again performed best on the test sample (silhouette = 0.46, versus 0.35 for K-Prototypes, 0.04 for KAMILA, and 0.42 for LCA; Section F.4). FAMD with k-means was thus applied to the full analytic sample (n = 177,190). Silhouette width again peaked at k = 6 (silhouette = 0.444 in FAMD-reduced space; 0.378 on the Gower-distance subsample), with mean bootstrap Jaccard stability of 0.635. Cluster sizes and defining features are summarized in Table 6.4 and visualized in Section F.5.

Table 6.4: Question B clustering solution characterization summary (n = 177,190).

Cluster	n (%)	Fixation	Stability	Tibial symmetry	Other features
1	63,789 (36.0%)	Cemented (98.8%)	PS (43.2%)	Symmetric (100%)	No patella (56.8%)
2	25,219 (14.2%)	Cementless (99.9%)	AS (50.9%)	Symmetric (99.9%)	No patella (79.2%)
3	2,700 (1.5%)	Cemented (99.6%)	VVC (46.1%)	Symmetric (63.1%)	Femoral stem (59.7%)
4	1,655 (0.9%)	Cemented (52.7%)	CR (40.7%)	Symmetric (100%)	Rotating mobility (99.5%)
5	43,345 (24.5%)	Cemented (99.8%)	PS (87.3%)	Asymmetric (94.7%)	Patella resurfaced (71.8%)
6	40,482 (22.8%)	Cemented (100%)	MP (85.1%)	Asymmetric (100%)	No patella (62.5%)

Abbreviations: AS = anterior-stabilized; PS = posterior-stabilized; VVC = varus-valgus constrained; CR = cruciate-retaining; MP = medial-pivot.

6.4.6 Question B: Cluster Characterization

Although implant model was not supplied to the clustering algorithm, femoral model retained a moderate-to-strong residual association with the resulting clusters (Cramér's V = 0.60, Fig. 6.2). Submitting province showed a strong association (V = 0.23), comparable in magnitude to Question A. Sex (V = 0.08) and diagnosis (V = 0.04) again showed very small associations. Other implant features supplied to the clustering algorithm with no-

table associations included: femoral stem use (V = 0.76), tibial fixation (V = 0.97), insert mobility (V = 0.99), and tibial component symmetry (V = 0.97).

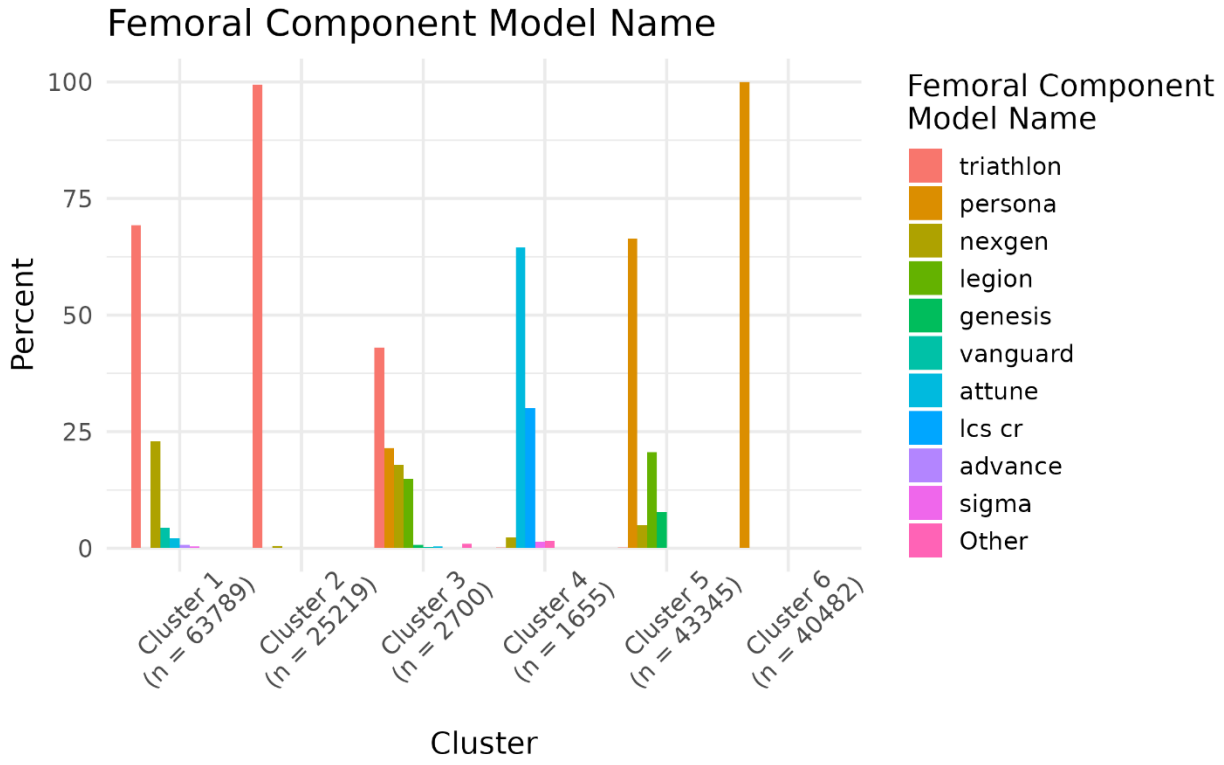


Figure 6.2: Question B clusters femoral model name distributions. Note: model name was not included as an input variable in this clustering analysis.

Tibial and femoral AP/ML ratio, used directly as clustering inputs in this specification, showed large effect sizes ($\eta^2 = 0.75$ and 0.67, respectively); insert thickness showed a small-to-moderate effect ($\eta^2 = 0.095$); age showed a small effect ($\eta^2 = 0.015$); and fiscal year showed a larger effect than in Question A ($\eta^2 = 0.076$).

Multinomial logistic regression (Cluster 1 as reference, full output in Section F.5) again showed statistically significant age, sex, and fiscal-year effects in most cluster comparisons. Male sex was associated with higher odds of membership in the primarily cementless cluster (Cluster 2 OR = 1.71, 95% CI: 1.66-1.76) relative to Cluster 1. Fiscal year was associated

with a shift toward Cluster 2 (primarily cementless cluster): compared with 2021, the odds of being in Cluster 2 rather than Cluster 1 were lower in 2019 (OR = 0.42, 95% CI:0.40-0.45) and 2020 (OR = 0.68, 95% CI: 0.65-0.72), but increased in 2022 (OR = 1.38, 95% CI: 1.31-1.44) and 2023 (OR = 1.89, 95% CI: 1.80-1.98). The overall model fit was low but somewhat higher than in Question A (McFadden pseudo-R^2 = 0.036; multiclass AUROC = 0.601).

6.4.7 Comparison of Question A and Question B Cluster Solutions

Cross-tabulating the Question A and Question B cluster assignments showed a strong overall association (Cramér's V = 0.712) but only moderate raw agreement (adjusted Rand index = 0.524). As shown in Table 6.5, the largest Question A cluster (Cluster 6, Persona-dominant, n = 69,773) split across two Question B clusters, with 58.0% falling into Question B Cluster 6 and 41.2% into Question B Cluster 5. The largest Question A cementless cluster (Cluster 1, predominantly Triathlon, n = 41,610) also split across two Question B clusters (60.3% into Question B Cluster 2; 38.6% into Question B Cluster 1). Conversely, 93.0% of Question A Cluster 2 (Triathlon, cemented, PS) mapped to a single Question B cluster (Cluster 1), and 99.7% of Question A Cluster 5 (Attune) mapped to a single Question B cluster (Cluster 4).

Table 6.5: Question A and B cluster cross-tabulation.

		Question B Cluster					
		1	2	3	4	5	6
Question A Cluster	1	16,046	25,106	369	0	89	0
	2	47,743	98	1,285	1	2,192	2
	3	0	0	25	64	0	0
	4	0	15	450	0	12,337	0
	5	0	0	5	1,590	0	0
	6	0	0	566	0	28,727	40,480

6.4.8 Sex-Disaggregated Analysis

Repeating the Question B clustering pipeline separately by sex, using K-Prototypes as the best-performing method on each sex-stratified test sample (Section F.6), yielded a different optimal number of clusters for men and women. Among male procedures (n = 70,804), a three-cluster solution was optimal (silhouette = 0.456; mean bootstrap Jaccard = 0.763, exceeding the 0.75 stability threshold), with cluster size distributions of 17.6%, 47.5%, and 35.0%. Among female procedures (n = 101,123), a four-cluster solution was optimal (silhouette = 0.314; mean bootstrap Jaccard = 0.594, below the 0.75 stability threshold), with cluster size distributions of 23.3%, 28.4%, 22.9%, and 25.4%.

Within each sex-stratified clustering solution, the categorical variables driving cluster separation differed. Among the male cohort, tibial fixation was by far the strongest differentiator (Cramér's V = 0.95): Cluster 1 (17.6%) was cementless (99.3%), while Clusters 2 and 3 (47.5% and 35.0%) were both cemented, with insert stability a secondary factor (V = 0.51). Among the female cohort, no cluster was cementless-dominant; instead, patellar resurfacing (V = 0.58) and insert stability (V = 0.61) were the strongest differentiators, while fixation method was comparably weak (V = 0.44). Femoral and tibial AP/ML ratio showed large effect sizes in both strata (male $\eta^2 = 0.66$ and 0.65; female $\eta^2 = 0.64$ and 0.86). Submitting province showed an identical, strong association with cluster membership in both sexes (V = 0.28), and most responsible diagnosis showed a negligible association in both (V = 0.01). Patient age was a weak predictor of cluster membership in both groups, and especially weaker among women (male $\eta^2 = 0.012$; female $\eta^2 = 0.001$).

The multinomial logistic regression models (Section F.6) showed similar, minimal overall explanatory power between sexes (male: McFadden pseudo-$R^2 = 0.025$, multiclass AUROC = 0.597; female: McFadden pseudo-$R^2 = 0.019$, multiclass AUROC = 0.573), and in both models, fiscal year was a stronger predictor than age. However, the cluster showing the largest temporal shift differed by sex. In the male cohort, the cementless cluster grew modestly over the study period (OR = 0.73, 95% CI: 0.68-0.79 in 2019 to OR = 1.16, 95% CI: 1.09-1.24 in 2023, relative to the largest cemented cluster). In contrast, in the female cohort, membership to the medial-pivot, antioxidant-loaded polyethylene cluster (Cluster

4) grew more sharply (OR = 0.51, 95% CI: 0.48-0.54 in 2019 to OR = 1.63, 95% CI: 1.54-1.71 in 2023, relative to the reference cluster), while the largest standard cemented, PS cluster (Cluster 3) declined over the same period (OR = 1.23, 95% CI: 1.16-1.30 in 2019 to OR = 0.78, 95% CI: 0.74-0.83 in 2023).

6.5 Discussion

This analysis applied FAMD and the K-means clustering algorithm to a dataset of 177,190 primary TKA procedures using two input-variable sets: one including the implant model name (brand name, Question A) and the other excluding model name but including the AP/ML ratios of the femoral and tibial components as an implant-design proxy (Question B). This aimed to address whether groups of complete implant configurations (i.e. selection of various implant features across the tibial baseplate, femoral, tibial insert, and patellar components) existed within the dataset and whether these groups were driven by functional configuration differences or model name. Both Question A and Question B clustering analyses resolved to a six-cluster solution with moderate internal validity (silhouette 0.44-0.53 in FAMD-reduced space) and moderate cluster stability (Jaccard 0.64-0.69). Question A clustering showed that across the 6 distinct clusters, most procedures fell into three clusters dominated by distinct manufacturers/models. Question B produced similar results, with 6 clusters emerging, with strong associations with specific models, despite not providing model names as a clustering input. Demographic factors such as patient age, sex, province, and year of surgery were examined in relation to cluster membership. Year of surgery was the strongest factor predicting cluster membership, suggesting that patient-specific factors (e.g., sex, age) showed comparatively limited associations with cluster membership. Overall, these findings suggest TKA implant selection may reflect a relatively structured set of prescribing patterns, rather than patient-specific selection. This perhaps supports treating implant selection as a distinct area of study, extending clustering approaches that have primarily been applied to comorbidity and outcome data in orthopedics and clinical informatics more broadly [10,19,24,38] to individual implant component configurations.

6.5.1 Model Versus Design Driven Variation

The comparison between Question A and Question B showed a moderate association between the cluster assignments. The Cramér's V value of 0.712 indicated that manufacturer/model identity and functional design configuration are strongly associated, and the residual association between femoral model and the Question B clusters (V = 0.60), despite model name being excluded from that analyses' input variables, suggests that brands tended to align with specific functional characteristics. However, the adjusted Rand index of only 0.524, and the fact that the two largest Question A clusters were split across two different Question B configuration profiles, suggests that brand identity may not fully determine functional configuration. For example, Persona, the dominant model of Question A Cluster 6 (n = 69,773, 39.4% of total cohort) split 58.0/41.2% across two Question B clusters that differed in both stability type and patellar resurfacing: one predominantly posterior-stabilized with patellar resurfacing in 71.8% of cases (Question B Cluster 5), and the other predominantly medial-pivot with patellar resurfacing in only 37.5% of cases (Question B Cluster 6). A similar split occurred for the largest Triathlon-dominant cluster (Question A Cluster 1, n = 41,610, 23.5% of the cohort). This cluster was divided 60.3/38.6% between a primarily cementless, anterior-stabilized cluster (Question B Cluster 2) and a cemented, posterior-stabilized cluster (Question B Cluster 1). This suggests that these opposite fixation method and stability type TKA configurations were grouped within a single, predominantly model name-defined Question A cluster. Thus, these splits suggest that Question B clustering provided a more granular picture than a simple brand-level cluster finding would suggest. This finding also supports the original motivation for running Question A and Question B in parallel; had only the Question A variable set been used, the design-level heterogeneity within a single model name may have been missed, and the resulting clusters could have been interpreted as purely brand-driven artifacts.

6.5.2 Provincial & Demographic Variation

Submitting province showed a strong association with cluster membership in both Question A and Question B analyses (Cramér's V = 0.23-0.26). Further investigation (Section F.3)

traced part of this association to a near-single-supplier pattern in one province, where 98% of procedures used a single femoral model. This is consistent with earlier CJRR reports of substantial provincial variation in implant utilization, which is not largely explained by patient demographics (Chapters 4 and 5) [5]. These clustering findings suggest a similar scenario wherein procurement differences and manufacturer concentration, may contribute to the province-level clustering observed. The literature has reported similar findings, including survey-based accounts of implant selection in which surgeon selection choices may be limited by institutional or jurisdictional contracts [6], and with more recent evidence that other non-patient factors such as institutional norms and adoption of new surgical technology such as robotics, shape implant selection independent of clinical indication [7].

Despite a very large sample size producing statistically significant demographic associations, the effect sizes were consistently small. For Question A and Question B cluster associations with sex, Cramér's V only ranged from 0.03 to 0.08. Multinomial regression models using age, sex, and fiscal year similarly explained little variation in cluster membership (McFadden pseudo-R^2 = 0.018-0.036). This suggests that patient sex and age were weak predictors of which implant configuration a patient received. These weak patient-factor associations are consistent with those reported in previous CJRR analyses (Chapters 3 and 4), but contrast with the more substantial sex and race-related differences previously documented in the literature [8,9]. The one demographic pattern that recurred across both Question A and Question B analyses was slightly higher odds of cementless-cluster membership among male patients (OR = 1.1 to 1.7 depending on the cluster comparison). This pattern was directionally consistent but small, relative to the much larger fiscal-year effect on the same cluster, and thus, perhaps, it should be treated as a signal to monitor this trend rather than as evidence of a clinically meaningful selection bias. This finding differs somewhat from previous CJRR analyses (Chapter 3), in which sex-based differences in fixation were more pronounced. One possible explanation is that considering the full TKA configuration, rather than examining fixation type in isolation, captures more nuanced patterns in fixation practices. In contrast, time was a more clearly interpretable driver of cluster composition. The relative share of the cementless/anterior-stabilized cluster increased steadily from 2019 to 2023. This finding is consistent with the

broader shift toward cementless fixation previously observed in Canadian registry data and globally (Chapter 3) [5,39], but in this analysis, the trend is shown in an overall change in cluster composition rather than in a single pre-specified fixation variable.

6.5.3 Clustering Method Performance

The resulting silhouette width values from the Question A and Question B clustering (0.33-0.53 across methods and specifications) were broadly consistent with, and in some cases exceeded, values reported for unsupervised clustering of large, mixed-type clinical and registry datasets in the literature [40]. Comparable electronic health record clustering studies have reported scores below 0.5, with some as low as 0.2 [40,41]. FAMD with k-means resulted in better performance metrics (Jaccard coefficient, silhouette width) than K-Prototypes, KAMILA, and LCA, consistent with existing clustering studies in which k-means-family methods have performed competitively with, or better than, latent class and kernel-based alternatives on internal validity metrics [12]. LCA's Bayesian Information Criterion continued to decrease without a clear minimum through k = 2-10 in both Question A and Question B. Although the LCA solutions showed moderate cluster separation (silhouette widths of 0.474 for Question A and 0.425 for Question B), they showed poor bootstrap stability, with Jaccard coefficients of only 0.106 and 0.138, respectively. This instability, and the documented tendency of BIC to impose a relatively weak complexity penalty at very large sample sizes, suggests that the continued decline in BIC with increasing numbers of classes did not necessarily indicate increasingly meaningful or reproducible structure [28]. Thus, despite the reasonable separation of the LCA-derived clusters, the lack of stability at higher-dimensional solutions supported relying on the more stable FAMD with k-means approach rather than selecting the nominal BIC-minimizing LCA solution. Bootstrap Jaccard stability for the FADM with k-means, six-cluster solutions (Jaccard = 0.635-0.693) was just below the 0.75 threshold conventionally associated with high stability [14,30]. Nevertheless, this level of cluster reproducibility is broadly consistent with other large mixed-data clinical clustering studies, where moderate stability is typical [15].

6.5.4 Sex-Disaggregation Structure

Sex-stratified re-clustering using the Question B input variables converged on different optimal numbers of clusters for the male cohort (k = 3) and the female cohort (k = 4). The female clustering solution had notably lower stability (Jaccard = 0.594, below the pre-specified threshold) than the male solution (Jaccard = 0.763). This could reflect greater heterogeneity in implant configurations used among female patients or perhaps reflects the somewhat larger sample size of this cohort (or both). Given the modest stability of the female cohort clustering solution, this finding should likely be interpreted as a possible area for further examination rather than reliable evidence of sex-based differences in the structure of implant selection.

The sex-disaggregated analysis revealed patterns that the pooled Question B model did not capture. While the pooled analysis reported only slightly higher odds of cementless-cluster membership among men (OR = 1.71, 95% CI: 1.66-1.76), disaggregation showed a more fundamental difference. Fixation method emerged as a predominant organizing feature of implant selection among male clusters but not in the female clusters. Tibial fixation strongly separated clusters in the male cohort (Cramér's V = 0.95), producing a clearly cementless cluster, whereas the female cohort had no cementless-dominant cluster and the fixation association was comparatively weak (V = 0.44). Instead, among female cohort clusters, patellar resurfacing (V = 0.58) and insert stability (V = 0.61) organized the structure more strongly.

The stratified analysis also had markedly different temporal trends. The pooled Question B trend toward cementless/anterior-stabilized designs appears largely male-driven, with cementless-cluster odds increasing from 2019 to 2023. In the female cohort, the fastest-growing cluster over the same period was instead a cemented, medial-pivot, antioxidant-loaded-polyethylene configuration (OR = 0.51 in 2019 to OR = 1.63 in 2023). These findings suggest distinct patterns of technology adoption by sex that would not have been visible, or at best would have been deflated, in a pooled fiscal-year effect centred on a cementless-dominant cluster. Thus, fixation adoption over time does not appear to follow a single trajectory in this cohort, but rather two sex-specific trends.

Notably, sex disaggregation did not strengthen the overall performance of the multinomial regression models. The pseudo-R^2 and AUROC in both sex-specific analyses were similar to those of the pooled model. Therefore, while the sex-specific models did not perform better overall, they revealed differences in the structure of implant selection that may be obscured when female and male populations are analyzed together.

Moreover, this distinction relates to the TKA demographic biases noted in the literature [8,9]. Conducting both pooled and sex-specific analyses showed that substantial overlap in cluster membership between sexes can coexist with meaningful differences in how implant configurations are structured within female and male patients.

6.5.5 Strengths & Limitations

This study benefited from a large, multi-year, national registry dataset, and a parallel Question A/Question B design that enabled model-driven and design-driven clustering structures to be distinguished. This approach addressed a relatively understudied aspect of orthopedics, where research has largely focused on individual implant attributes or outcomes rather than patterns of complete component configurations. The use of multiple clustering methods and validation approaches further supported assessment of the robustness of the identified configurations.

Nevertheless, several limitations warrant consideration. CJRR coverage varied by province and was not complete even in jurisdictions with mandatory reporting [5], so cluster composition may not fully represent national practice. Cluster stability for the selected solutions, while acceptable, did not reach the 0.75 threshold for either the Question A or Question B (pooled) solutions, indicating these clustering solutions were not highly reproducible across resampling. The low model fit of the demographic multinomial models and small effect sizes of demographic associations also limited equity-related conclusions. This suggests that unmeasured factors, such as surgeon preference and hospital-level procurement, which were not available in this dataset, may account for more variation in cluster membership than the patient-level factors included. Moreover, the cross-sectional,

observational design did not support causal analyses about why particular clusters were associated with particular provinces, years, or demographic groups.

6.5.6 Conclusions and Future Directions

These findings suggest that TKA implant selection in the CJRR followed recognizable practice patterns shaped more so by implant model and underlying functional design than by patient characteristics. The emergence of the same six general implant configurations, regardless of clustering with model information, suggests that implant selection reflects meaningful functional design patterns rather than implant model alone. The strong association between model and design also highlights an important real-world constraint: manufacturer product lines may limit which combinations of fixation, stability, articulation, and resurfacing features are available to surgeons, as not all options are currently available under all manufacturers or models.

Aside from implant characteristics, patient factors such as age and sex were relatively weak predictors of implant configuration compared with province and fiscal year. This suggests that other factors such as procurement, institutional practice, and evolving surgical preferences may drive more of the observed variation. The differences identified in the sex-disaggregated clustering further suggest that pooled analyses can obscure meaningful patterns in implant selection.

Taken together, the findings support further investigation of procurement practices and continued monitoring of demographic patterns, while also suggesting perhaps that we need to reconsider how TKA implant use and performance are currently evaluated. Future analyses should incorporate sex-disaggregated analyses where appropriate and examine TKA trends by complete system configuration rather than individual implant characteristics in isolation. Moreover, future analyses may benefit from including hospital and surgeon identifiers, which could help determine whether observed variation reflects institutional availability, surgeon preference, or both.

6.6 References

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Chapter 7

Conclusions and Recommendations

7.1 Conclusion

7.1.1 Overview

This section will not restate many of the results, methodological, or limitation details described in the manuscripts of the previous sections. This section simply synthesizes the conclusions across those manuscript sections and provides final thoughts and conclusions from these analyses.

This thesis aimed to (1) develop and evaluate data-quality tools, including a standardized implant reference library and validation logic, to improve the reliability of manufacturer- and model-level analyses; (2) characterize national and provincial trends in TKA fixation, patellar resurfacing, implant stability, and implant manufacturer and model use within the CJRR, comparing these findings with other national arthroplasty registries where appropriate; and (3) use clustering methods to identify latent implant prescribing patterns and assess whether patient and institutional factors predict cluster membership.

7.1.2 Objectives & Hypotheses

The data quality objective was addressed through the development of an open-source implant reference library. As hypothesized, this tool substantially improved the usability of the CJRR dataset and demonstrated potential for future applications, including retrospective data validation. Although the library was not without limitations, including missing data and opportunities for further refinement, its development demonstrated the value of leveraging open-source resources and publicly available databases to strengthen registry data quality and research capacity.

Consistent with other hypotheses, these analyses of CJRR primary TKA data from 2019 to 2023 showed a notable increase in cementless fixation, with greater use among male and younger patients. As hypothesized, variation in patellar resurfacing and insert stability, as well as increased posterior stabilized insert utilization specifically in procedures with patellar resurfacing, was observed. Substantial provincial variation was also observed across fixation method, patellar resurfacing, stability constructs, and manufacturer- and model-level implant selection, consistent with the hypothesized influence of procurement practices and Canada's decentralized healthcare system. Finally, clustering analysis identified six distinct TKA prescribing configurations that varied primarily by fixation, stability, and implant model, supporting the hypothesis that distinct prescribing patterns exist. However, patient-level factors did not substantially explain cluster membership, suggesting that other factors, potentially including surgeon, institutional, or procurement-level characteristics, may play a greater role in determining implant selection.

7.1.3 Conclusions

Each of the preceding chapters examined a different area of knee arthroplasty implant use in the CJRR. Individually, each answers separate questions, but read together they describe a single evolving picture of how implants are built, marketed, and selected in Canada.

The data quality pipeline developed in Chapter 2 provided a foundation for improving

the granularity and usability of the data for the other analyses. The standardized dataset the pipeline produced validated the data for the trends in fixation, resurfacing, stability, sizing, manufacturer share, and clustering reported in this thesis. Thus, any pipeline limitations, or instances where it could not fully resolve ambiguity in the original data, carried into the downstream analyses. This should thus be noted as a standing caveat across the results that follow rather than repeated at each turn.

Fixation, patellar resurfacing and implant stability showed three different views of how knee implant design usage evolved over the study period. The increase in cementless use coincided with a decrease in patellar resurfacing and posterior stabilized stability designs, while medial pivot design use increased. These simultaneous shifts may suggest a shared driver; perhaps evolving surgical philosophy, evidence from the literature, or changes in what is available on the market. In contrast, the use of cruciate retaining insert stability designs stayed broadly consistent over the study period. This may suggest that TKA selection choices are not a single grouped decision but several independent ones, each influenced by different factors.

Manufacturer trends provided information on the TKA market landscape in which the above trends occurred. Shifts observed in market share and trends of specific models over the study period helped to distinguish whether a given design trend reflected a genuine shift in clinical practice or partially reflected manufacturer/model composition in Canada at a given time. For example, Stryker Triathlon alone accounted for most of the fixation shift toward cementless designs, suggesting the trend is at least partly influenced by market composition rather than purely clinical indications.

The clustering analysis (run once with model name included and once without) provided an overarching check on the findings above. With model name included, clusters largely recovered known model lines, which validated that the clustering approach picked up real design structure rather than noise. Without model name, the clusters showed what structure exists in the design-feature data on its own terms: the results still broadly tracked the model identities, suggesting each model has a genuinely distinct design, but there was still some mixing across brands, suggesting convergent design across manufacturers, where competitors converge on similar feature combinations regardless of model label. Read

against the fixation, resurfacing/stability, and manufacturer findings above, this comparison helps distinguish whether design trends are manufacturer-driven or something closer to an industry-wide pattern.

Together, these threads support a couple of overarching themes about the Canadian TKA landscape. First, design convergence across brands: the clustering without model name (Question B in Chapter 6) showed that after removing model identity, the same functional categories (e.g. cemented/posterior stabilized, cementless/anterior stabilized, or cemented/medial pivot) still emerged, recurring across different models rather than into model-specific groups. However, the fixation, resurfacing and sizing findings complicate the apparent convergence. The functional features that organized implant selection were not equally important across patients. Fixation method distinguished implant choices among male patients, but barely differentiated implant configurations among females, for whom patellar resurfacing and stability type played greater organizing roles. Thus, convergence across manufacturers on broad functional categories does not necessarily mean that these categories carry the same importance across patient groups. Moreover, sizing/shape (the AP/ML ratio) remained closely associated with specific models even when model name was excluded from clustering, suggesting that while manufacturers may converge on similar broad functional categories, individual implant systems retain distinct geometric "signatures" within those categories.

Second, market consolidation was apparent, as most procedures concentrated in only a few systems, and in at least one province a single manufacturer captured nearly the entire market. However, even after the model name was dropped from clustering entirely, manufacturer identity remained moderately recoverable from functional design, suggesting that the dominant systems carry a real, somewhat distinctive functional signature. Thus, consolidation may not be purely arbitrary; it may be anchored in some genuine design differentiation. But recovery was incomplete, complicating this interpretation. The dominant single model clusters didn't map to one distinctive design each. They included more than one functional configuration within a model name. Taken together, this suggests that design differentiation may only partly explain the market consolidation. Much of it may be influenced by manufacturer breadth and procurement practices, which may have little

to do with the device itself.

Third, there was a recurring gap between what was available in the registry data and what likely contributed to the variation observed. Important surgical and institutional data such as information on PCL resection, surgeon identifiers, or hospital identifiers were not available. The unexplained variation noted consistently across the analyses in this thesis suggests that these unmeasured surgical and institutional characteristics may capture some of the factors driving the variation.

7.2 Recommendations

7.2.1 Registry Data Infrastructure and Data Quality

The data quality issues documented in this thesis point to a set of concrete opportunities to strengthen the registry's data infrastructure. Several of the experiences described below are specific to the CJRR's current processes; others reflect challenges that are well documented across patient registries internationally and are presented here as generalizable considerations [1–6].

Adoption of an Open-Source Implant Reference Library

The open-source reference library developed in this study (Chapter 2) offers CJRR-affiliated researchers a method of validating and supplementing implant-level data without an International Prosthesis Library (IPL, which contains component-level data including model name, catalogue number, material, and design features) subscription. Plans have been discussed within the International Society of Arthroplasty Registries for a next-generation IPL to be released in 2027, which could reduce the need for an independent, open-source library of this kind. However, until this resource is publicly available, and for researchers or institutions unable or unwilling to purchase an IPL subscription, an open-source alternative such as the one presented here remains a practical option. It is also worth noting that the open-source reference library already exceeds the granularity of some CJRR-native fields: for

example, the CJRR currently groups cruciate-retaining, posterior-stabilized, medial-pivot, and other insert designs together under a single "minimally stabilized" category, whereas the open-source reference library preserves this distinction, illustrating that an independently maintained library can extend rather than merely replicate existing registry classifications. Moreover, unlike other libraries that require additional manufacturer-submitted information to update the library with new implants, this public-data-base-sourced, automated pipeline allows easier version updates, as the pipeline can simply be re-run on the databases, pulling information for catalogue numbers not currently in the library.

Synoptic Reporting and Automated Validation checks

Barcode scanning, already implemented in CJRR data entry, meaningfully reduces manual-entry error for product and lot number fields by populating them directly from the implant packaging label rather than requiring free-text or keyboard entry [7,8]. However, barcode formats are not standardized across manufacturers, and scanning is not possible for every product; where a barcode is missing, damaged, or non-standard, manual entry remains necessary in the current process, reintroducing many of the errors that scanning is intended to prevent.

Manual recording is most vulnerable in the legacy paper-based workflow, which, although has been formally retired since 2013 [9], recording errors from before this time may persist in the CJRR data. In this legacy, paper-based workflow, a sticker from each implant component's packaging, along with any cement sticker used, was placed into a corresponding labelled box on the paper form. This process had no structural safeguard against sticker misplacement, could not distinguish which specific component a cement sticker was intended for when more than one is present, and provided no mechanism to prevent submission of an incomplete form. If a surgeon inadvertently opened the wrong package, the resulting sticker may still have been placed on the form for inventory-tracking purposes even though it did not correspond to the component actually implanted. This offers one plausible mechanism, in addition to those already proposed in Chapter 2, for the duplicate component-type entries and catalogue-number misclassifications observed

in the CJRR dataset independent of any downstream barcode-scanning or DAD/NACRS abstraction errors.

Extending barcode-driven automation further would address several of the noted data quality challenges directly. Rather than requiring manual selection, the manufacturer field, along with component type and JOINT_COMP, should be auto-populated directly from the scanned barcode via linkage to an IPL or an equivalent reference library, consistent with the approach already used by the Dutch Arthroplasty Register [10]. Submissions containing multiple barcodes mapped to the same component type (e.g., two tibial baseplates) should be automatically rejected, prohibiting submission until the correct codes are scanned, preventing the duplicate-component pattern documented in Chapter 2 at the point of entry rather than requiring downstream correction. Where a barcode is not recognized in the reference database, data entry staff should be presented with a standardized, validated list of approved devices (via Health Canada Medical Device Active License Listings (MDALL)), using dropdown selection or predictive text, rather than free text, and submissions pairing an invalid manufacturer-model combination (for example, a model name that does not correspond to the selected manufacturer) should be flagged and rejected before submission. Predictive, real-time validation of this kind is already used to good effect by the AOANJRR [11,12].

Beyond implant identification, the broader clinical and surgical fields relevant to CJRR analyses, such as surgical approach, implant model name, PCL status or resection, fixation technique, and cement use per component, remain largely inconsistent or absent, aligning with the general finding that unclear data definitions and inconsistent translation of information from clinical records into registry fields are leading causes of registry error [13]. Synoptic reporting, in which clinicians or abstractors complete structured, mandatory fields with standardized response options rather than free text or selection without validation, is well established as a means of improving the completeness, consistency, and downstream interoperability of clinical documentation. Canada has already demonstrated success in this at national scale in the Canadian Partnership Against Cancer's synoptic surgical and pathology reporting initiatives, which have been rolled out across multiple provinces and are credited with improving data quality and supporting a national learning

health system in cancer surgery [14]. A similar structured-entry approach for the CJRR's clinical and surgical fields, integrated with the IPL/barcode-driven automation described above for implant fields, would reduce the free-text and variable naming inconsistencies burden identified throughout this article and support the kind of automated, field-level validation, range checks, mandatory-field checks, in-line data definitions, and conditional fields that only appear when relevant, that has been identified as central to high-quality registry data collection elsewhere [13].

Nevertheless, any such change must be weighed against its effect on surgeon workload. Surgeon-entered data can offer richer, more clinically nuanced information than facility-level abstraction, and direct clinician involvement is associated with greater investment in data quality; but surgeons already carry a substantial clinical workload, and adding structured data-entry requirements risks rushed or incomplete entry if not carefully designed. Experience with synoptic reporting in other Canadian surgical contexts suggests that initial adoption burden can be substantial but tends to normalize as templates are refined and integrated into clinical workflow, and that delegating non-clinical-judgment fields, such as implant identifiers, to trained assistants or facility data staff can offset some of this burden without sacrificing clinical nuance for fields that require it [14]. Given this, a full mandatory overhaul of the CJRR submission process is not recommended as an immediate first step. A phased approach, incorporating input from surgeons with experience using synoptic reporting to develop and pilot synoptic templates for a limited set of high-value clinical fields at selected high-volume, well-resourced centers before expanding nationally, and maintaining and extending the existing barcode infrastructure for implant fields throughout, would deliver meaningful data quality gains while controlling implementation cost and managing the risk to reporting compliance that a more disruptive change could introduce.

Standardized Variable Definitions and Minimum Data Sets

Several fields would benefit from standardization that could likely be implemented with only modest effort, even retrospectively rather than at the point of collection. Compo-

nent type names should be standardized across submission pathways and the IPL alike, given the variation documented in Chapter 2 (e.g., "Knee-Femoral" versus "Femoral Component"). Model name formatting in the IPL, including hyphenation and capitalization, should similarly follow a consistent convention; comparable standardization efforts for implant identification elsewhere have been shown to improve cross-registry usability [15].

New or expanded fields would also improve research value. A field identifying which components were used with cement, rather than a single procedure-level cement flag, would resolve ambiguity in the current data and allow better identification of cementless or hybrid procedures, as many cementless models are indicated for use both with and without bone cement, so implant model alone cannot guarantee fixation method. Surgical information such as PCL resection and surgical approach should be also added to the minimum data set; because DAD and NACRS abstracts already draw on detailed CCI procedure codes, at least partial capture of these fields could likely be abstracted from existing DAD/NACRS submissions without new clinician-facing burden, though the legacy CJRR pathway, which does not collect CCI codes [14], would require updating or retirement to benefit equally.

The hospital teaching-status classification discussed in Chapter 2 offers a further example of a field that would benefit from cross-validation. CIHI's current designation draws on provincial ministry submissions, the Canadian MIS Database, and CIHI's own Organization Index [26], but, as the Manitoba/Concordia Hospital case illustrates, this administrative designation does not always align with a hospital's actual academic activity. Cross-validating or supplementing this field with an independent, authoritative source, such as the Royal College of Physicians and Surgeons of Canada's accreditation records for orthopedic surgery residency programs [16], would allow institutional classification to be verified against a criterion more directly tied to teaching activity than ministry designation alone.

More broadly, adopting minimum data set elements recommended by international bodies such as the International Society of Arthroplasty Registries would improve the CJRR's interoperability with other national registries and support cross-registry comparisons already achieved by registries with more established data standards [2,17].

Improved Multi-System Integration

Combining submissions from the legacy CJRR system, DAD, and NACRS improves alignment with existing hospital documentation workflows but, as shown in Chapter 2, also introduces systematic inconsistency. For example, fields derived from CCI procedure codes are populated for DAD/NACRS submissions but are structurally absent from the legacy stream, which does not capture CCI codes at all [9,18]. Because CJRR data collection has already been moving toward DAD- and NACRS-based submission, with NACRS accepted since 2022–2023 [9], completing this transition, either by requiring legacy submitters to migrate to CCI-code-based abstraction or by formally retiring the legacy pathway, would resolve this specific source of missingness going forward rather than requiring continued reconciliation between structurally different data sources. Any such transition should be paired with the standardized field definitions and structured data capture recommended above, to ensure that consolidating submission pathways also resolves, rather than simply relocates, the underlying data quality issues.

Generalizable Registry Challenges and Broader Context

The issues addressed above are not unique to the CJRR. Missing and incomplete entries are a well-documented problem across patient registries: an early evaluation of the CJRR itself found a national reporting rate as low as 41% before mandatory provincial submission expanded coverage in the years that followed [17]. Comparable completeness challenges have been reported for other registries internationally [1,3,5]. Consent and privacy requirements, while necessary, can introduce their own bias. Requiring individual informed consent for a Canadian stroke registry was found to systematically under-enrol patients who were more severely affected or unable to consent, threatening the representativeness of the resulting data [4]. Balancing these requirements against the public health value of more complete registry data remains an active policy question for the CJRR and other registries alike [4,17]. Lack of standardization of core data elements, resource and funding instability, and duplication between registries and other administrative or clinical data systems, including electronic medical records, are similarly recognized as recurring, cross-cutting challenges

for registries in general [2,6].

The literature on registry best practice points toward solutions consistent with those proposed above, including, multidisciplinary stakeholder engagement and clear governance [2]; adoption of internationally recognized data standards [2,17]; stronger integration with electronic medical records and emerging data capture technologies; stable, long-term funding models [2]; systematic quality assurance through audits, validation studies, and peer review [1,2]; and policy engagement to balance privacy protection with the public health value of registry research [4,17]. Canada has begun to act on several of these fronts: Canada's Drug Agency (CDA-AMC) has recently published national guidance and best-practice standards intended to improve data quality across the roughly 130 rare-disease and other clinical registries it has identified operating in Canada [6,19], and emerging efforts to better coordinate and share data across provincial and specialty-specific registries reflect a broader national push toward more integrated, higher-quality registry infrastructure [6]. The recommendations proposed in this section, an accessible implant reference library, IPL/barcode-driven and synoptic structured data capture, standardized variable definitions, and improved multi-system integration, are intended as a concrete, CJRR-specific contribution to that broader effort.

7.3 Model-Level and Subgroup-Level Reporting

Standard CJRR reporting stratifies revision outcomes by broad categories such as fixation method, patellar resurfacing status, and implant stability classification. The clustering analyses in this thesis identified additional subgroups, based purely on implant design features, that cut across these standard categories (Chapter 6). This suggests that current registry stratification, while a reasonable starting point, may obscure clinically meaningful heterogeneity in outcomes. Thus, incorporating cluster-informed subgroup analysis into future annual reports, alongside standard categories, may allow the CJRR to surface performance differences that current groupings do not capture. Comparable model-level reporting is already standard practice in more established national registries, and the findings in this thesis reinforce the case for CJRR to move toward the same.

This would additionally align CJRR reporting with the minimum-checklist framework recently proposed by Hoogervorst et al., for evaluating the quality of evidence produced using registry data for device safety and performance. It recommends that registries define their approach to comparative performance analysis (e.g., benchmarking or non-inferiority testing) and their threshold for outlier performance before implementing model-level reporting, along with documented methods for handling and reporting missing data and a defined quality-assurance/data-verification process [20].

7.4 Sex-Disaggregated Analysis

Throughout this thesis, various findings indicated sex-based differences, suggesting that sex may warrant greater attention as an important factor rather than often being considered solely as a variable to adjust for in analyses. Fixation choice and clustering-derived prescribing patterns both differed meaningfully by sex, perhaps reflecting anatomical factors (e.g. bone shape, bone mineral density, hormonal factors) that may influence implant performance [21–23]. Statistically controlling for sex risks averaging away exactly these effects rather than accounting for them. Adding sex-disaggregated analysis, as a standard CJRR reporting practice, may better reflect these differences and support more individualized, evidence-based implant selection.

7.5 Component Size Analyses

The variation in implant manufacturer and model utilization in Canada (Chapter 5) suggests a need for deeper investigation of differences across manufacturers and models. One notable area of difference between models is sizing. Various studies have reported substantial variation in the use of model sizes, as well as in overall component fit (component overhang or underhang) by sex [24–27]. Some studies have suggested that the current range of available sizes does not accommodate the anatomical dimensions of all patients [27]. Although not presented in this thesis, preliminary analyses of, specifically, tibial

component size utilization (as tibial component undersizing has been associated with a greater risk of complications [24, 25]), suggest substantial skewness in the sizes used, with female patients disproportionately receiving the smallest few available sizes. Investigation of the mediolateral and anteroposterior dimensions of implant sizes by model also showed substantial variation in the range of dimensions covered by a model's size portfolio and in the dimensional increments between sizes, suggesting that, depending on the manufacturer or model used at a given hospital, some patients may not have an adequate sizing option available. Thus, future work evaluating size differences between models and use patterns in TKA practice should be undertaken to inform the field of the potential need for additional sizing options, and to ensure hospitals understand how procurement decisions may affect patient care through implant fit.

7.6 Procurement Transparency and Health Equity

Other national registries have documented meaningful differences in revision rates across implant models [24–28]. In Canada, provincial procurement processes and group purchasing organizations can influence which implant models are available in a given hospital, independent of clinical evidence (Chapter 5). This raises a potential equity concern, as patient access to higher- or lower-performing implants should not depend on where in Canada they receive care. Greater transparency in procurement decision-making, and closer examination of how cost negotiations interact with implant selection, are warranted, as they may enable evaluation and inform the balancing of economic factors and patient-centred care. As mentioned above, model-level public reporting of revision rates would complement this, giving procurement decisions and patients a stronger evidence base.

7.7 Clinical Practice, Training, and Accountability

Much of the variation in implant selection documented in this thesis was not explained by the patient-level demographic variables available in CJRR. Then what does explain

it? Perhaps factors including surgeon training and institutional practice norms contribute to the variation. Surgeons have been reported to gravitate toward implants they were trained on, independent of comparative outcome evidence [29]. Potential avenues to address this pattern may include giving surgeons better access to registry findings, incorporating registry-based evidence into surgical training curricula, and building accountability practices, such as surgeon-level or hospital-level reporting, that support evidence-based rather than familiarity-based implant selection. However, establishing long-term performance comparisons between implant systems remains challenging as implant designs and surgical technologies continue to evolve. These measures are not intended to imply that familiarity-based selection reflects inappropriate surgeon intent; instead, they aim to ensure that surgeons have the information and structural support needed to act accordingly.

7.8 Research Infrastructure and Data Access

Finally, the CIHI Graduate Student Data Access Program used in this thesis to access de-identified, patient-level CJRR data has some constraints that may limit the kinds of analyses that can be validly conducted. The data from this program included joint-level identifiers but did not allow patient identifiers; thus, procedures in the same patient could not be identified. This undermines the core statistical assumption of independence. Improving this program to allow appropriately governed access to the identifiers or linkages required for legitimate, statistically sound research would allow graduate researchers to make greater use of registry data and would better support CJRR's broader research and knowledge-translation mission. It would also help ensure that the substantial time and effort CJRR's statistical teams invest in preparing data extracts, vetting outputs, and preparing the data translate into quality research findings that fully leverage the registry's data. Providing appropriate linkages to patient identifiers could therefore substantially increase the research value generated from these efforts.

7.9 Closing Statement

This thesis makes several contributions to the literature on TKA practice patterns, both internationally and within Canada. It provides a detailed characterization of TKA prescribing patterns across Canada, including trends in fixation method, patellar resurfacing, implant stability, and implant manufacturer and model utilization. The analyses also provide greater granularity than previously reported in Canadian Joint Replacement Registry (CJRR) reports or the broader literature on Canadian TKA. Examining patterns by sex, at the implant model level, and through clustering approaches provides a more nuanced understanding of how TKA implants are selected and used across the Canadian healthcare system.

Moreover, this work strengthens the data infrastructure available for future research by developing the open-source implant reference library. By improving the identification and classification of individual implants, this infrastructure enables more reliable and granular manufacturer- and model-level analyses and provides a foundation for future investigations using CJRR data. Together, these methodological and analytical contributions demonstrate the value of leveraging both public data sources and the vast amount of data already being collected through national registries.

Beyond describing practice patterns, the findings identify areas warranting further investigation, including potential variation in care across patient and regional demographics and possible inequities in TKA practices across the Canadian healthcare system. Future research should build on this work by linking prescribing patterns to clinical outcomes to determine whether observed differences in implant selection and surgical practice are associated with differences in patient outcomes, implant survivorship, or complications. Such outcome-based analyses may help identify opportunities to improve the consistency, quality, and value of TKA care in Canada.

Ultimately, the recommendations arising from this thesis are intended to support greater use of the data already being collected through the CJRR. Strengthening data quality, improving the granularity and accessibility of registry data for research, and linking practice patterns to patient outcomes can help transform routine data collection into actionable

evidence. In doing so, Canada can better understand how TKA care is being delivered, identify where improvements may be needed, and ensure that the substantial resources invested in the healthcare system translate into the best possible outcomes and value for patients and the public.

Finally, thank you for reading this thesis and, in the process, learning perhaps an excessive amount about knee replacements. To anyone who has made it all the way to this section: may you never need a knee replacement.

The End.

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Introduction

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Appendix A

Background: Supplementary Material

This appendix contains supplementary material for Chapter 1.

A.1 CJRR Data Collection Forms

Canadian Institute for Health Information

Institut canadien d'information sur la santé

For CIHI use only

Unique Identifier

CANADIAN JOINT REPLACEMENT REGISTRY

Knee Replacement Data Collection Form

Addressograph

Surgeon First Name

Surgeon Last Name

Has Patient Consent Been Obtained? ☐ Yes ☐ No **If no, please complete only surgeon first/last name and hospital name, and forward to CIHI.**

Patient First Name | Middle Initial | Patient Last Name

Provincial Health Card Number

Province Code

Birth Date (Y Y Y Y M M D D) Home Postal Code

Gender ☐ Male ☐ Female Height (cm) • Weight (kg) •

Hospital Chart Number Hospital Province

Hospital Name _____

Surgery Date (Y Y Y Y M M D D) Admission Date (if different from surgery date) (Y Y Y Y M M D D)

Wait Time Information

Referral Date **(New Patients Only)** (Y Y Y Y M M D D)

Date of First Consult **(New Patients Only)** (Y Y Y Y M M D D) Date of Decision for Surgery **(All Patients)** (Y Y Y Y M M D D)

Please Complete This Form by Checking (√) the Appropriate Box (es)

Side (Location)	***If bilateral, complete ONE form PER SIDE*** Unilateral ☐ Right ☐ Left Bilateral ☐ Right ☐ Left
Type of Replacement	***Check ONE only:*** ☐ Primary ☐ R1 ☐ R2 ☐ R3 ☐ >R3 ☐ Excision (not a revision)
Diagnosis Grouping (for primary replacement only)	***Check MOST RESPONSIBLE diagnosis to involved knee:*** ☐ Degenerative OA ☐ Inflammatory Arthritis ☐ Post Traumatic OA ☐ Osteonecrosis ☐ Infection ☐ Tumour ☐ Acute fracture ☐ Other _____
Reason(s) for Revision ☐ N/A **or** ➔ ↓	***Check ALL that apply to involved knee:*** ☐ Aseptic Loosening ☐ Infection—Single Stage ☐ Implant Fracture ☐ Poly Wear ☐ Instability ☐ Pain of Unknown Origin ☐ Infection—Two Stage ☐ Bone Fracture ☐ Osteolysis ☐ Unispacer ☐ Unresurfaced Patella ☐ Patella Maltracking ☐ Patella Failure ☐ Other _____
Previous Operations ☐ None **or** ➔ ↓	***Check ALL that apply to involved knee:*** ☐ Total Knee Arthroplasty ☐ Unicompartmental Arthroplasty ☐ Tibial Osteotomy ☐ Femoral Osteotomy ☐ Open Menisectomy ☐ Arthroscopic Menisectomy ☐ Patellectomy ☐ Ligament Repair ☐ Fracture Fixation ☐ Arthroscopic Debridement ☐ Other _____
Joint Deformity ☐ None **or** ➔ ↓	***Check ALL that apply to involved knee:*** ☐ Varus ☐ Valgus ☐ Flexion contracture ☐ If Any ≥15°
Surgical Approach	***Check APPROACH:*** ☐ Medial Parapatellar ☐ Lateral Parapatellar ☐ Intravastus ☐ Subvastus ☐ Other _____ ***Minimally Invasive (MIS)?*** ☐ Yes ☐ No
Special Steps ☐ None **or** ➔ ↓	***Check ALL that apply to involved knee:*** ☐ Lateral Retinacular Release ☐ Rectus Snip ☐ Quadriceps Turndown ☐ Tubercle Osteotomy ☐ Other _____
Antibiotic Use	***Will antibiotics be administered prophylactically?*** ☐ Yes ☐ No ***If yes, duration?*** ☐ ≤24 hours ☐ >24 hours
DVT Prevention	***Will DVT prophylaxis be given in hospital?*** ☐ Yes ☐ No ***If yes, check ALL that apply:*** ☐ Warfarin ☐ LMW Heparin ☐ ASA ☐ SC Heparin ☐ Pneumatic Stockings ☐ Foot Pump ☐ Other _____
O.R. Environment	***Check ALL that apply:*** ☐ Laminar Air Flow ☐ No Laminar Air Flow ☐ Body Exhaust ☐ Ultraviolet

CANADIAN JOINT REPLACEMENT REGISTRY **KNEE REPLACEMENT DATA COLLECTION FORM**

Femoral Component

Replaced?
☐ Yes ➔
☐ No ➔

Unicompartmental Prosthesis?
☐ Yes ☐ No
If yes,
☐ Medial ☐ Lateral ☐ Patellofemoral
Cemented? ☐ Yes ☐ No
If Cemented:
Porosity Reduction: ☐ Yes ☐ No
If Cementless, *Check ALL that apply*:
☐ Porous In-growth ☐ H. A. Coated
☐ Press-fit

Manufacturer See Legend Below
Femoral Component

Affix sticker(s) or catalogue and lot number beside the specific component. Do not include stickers for screws.
Sticker for Femoral Component

Tibial Component

Replaced?
☐ Yes ➔
☐ No ➔

Unicompartmental Prosthesis?
☐ Yes ☐ No
If yes,
☐ Medial ☐ Lateral ☐ Patellofemoral
All Polyethylene? ☐ Yes ☐ No
Mobile Bearing? ☐ Yes ☐ No
Cemented? ☐ Yes ☐ No
If Cemented:
Porosity Reduction? ☐ Yes ☐ No
If Cementless, *Check ALL that apply*:
☐ Porous In-growth Screws? ☐ Yes ☐ No
☐ H.A. Coated Screws? ☐ Yes ☐ No
☐ Trabecular Metal Screws? ☐ Yes ☐ No
PCL Retaining **Or** **PCL Sacrificing**
☐ Standard ☐ Post & Cam ☐ Constrained
☐ Medial Pivot ☐ Deep Dished ☐ Hinged
☐ Medial Pivot

Manufacturer Poly Insert

Tibial Base Plate

Sticker(s) for Poly (Insert)

Sticker(s) for Tibial Base Plate

Patellar Component

Resurfaced?
☐ Yes➔
☐ No➔

Cemented? ☐ Yes ☐ No
Type: ☐ Inset ☐ Onlay

Manufacturer Patellar Component

Sticker for Patellar Component

Modular Stem
☐ Yes ➔
☐ No ➔

Stems	**Femoral**	**Tibial**
Cemented	☐	☐
Cementless	☐	☐

Manufacturer Femoral Stem

Tibial Stem

Sticker(s) for Modular Femoral Stems

Metal Augments
☐ Yes ➔
☐ No ➔

Augments	**Femoral**	**Tibial**
Metal	☐	☐
Trabecular metal	☐	☐

Sticker(s) for Modular Tibial Systems

Cement Details

Cement Used?
☐ Yes ➔
☐ No ➔

For each item, Check ONE only:
Cement Name:
☐ Simplex ☐ Zimmer ☐ CMW ☐ Versabond
☐ Palacos ☐ Osteobond ☐ Cerafix ☐ Other _____
Antibiotics Added by Manufacturer? ☐ Yes ☐ No
Antibiotics Added by Surgeon? ☐ Yes ☐ No
***If Yes*, Antibiotic Name:**
☐ Tobramycin ☐ Vancomycin ☐ Gentamicin ☐ Erythromycin ☐ Other
Mixing Method: ☐ Vacuum-mixed ☐ Centrifuge ☐ Manually Mixed

Sticker for Cement Type

Bone Graft Used—Femur
☐ Yes ➔
☐ No ➔

Check ALL that apply:

	Autograft			Allograft	Bone Graft Substitute
	Iliac crest	Local bone	Other		
Structural	☐	☐	☐	☐	☐
Strut/Onlay	☐	☐	☐	☐	☐
Morselized	☐	☐	☐	☐	☐

Bone Graft Used—Tibial
☐ Yes ➔
☐ No ➔

Check ALL that apply:

	Autograft			Allograft	Bone Graft Substitute
	Iliac crest	Local bone	Other		
Structural	☐	☐	☐	☐	☐
Strut/Onlay	☐	☐	☐	☐	☐
Morselized	☐	☐	☐	☐	☐

Legend of Manufacturer Codes: 01 Biomet 02 Ceraver 03 J&J/DePuy 04 Sulzer/Centerpulse 05 Zimmer 06 Wright Medical 07 Smith & Nephew Richards 08 Stryker/Osteonic/Howmedica 99 Other

Formulaire disponible en français

Canadian Institute for Health Information
Institut canadien d'information sur la santé

For CIHI use only

Unique Identifier

Addressograph

CANADIAN JOINT REPLACEMENT REGISTRY

Knee Replacement Data Collection Form

Hospital Name _____

Surgeon First Name

Surgeon Last Name

Patient First Name

Patient Last Name

Gender ☐ Male ☐ Female

Provincial Health Card Number
Province Code

Birthdate **Y Y Y Y** **M M M** **D D**

e.g. 2012 APR 05

Home Postal Code

Hospital Chart Number

Surgery Date **Y Y Y Y** **M M M** **D D**

Please Complete This Form by Checking (✓) the Appropriate Box(es)

Side (Location)	Unilateral: ☐ Left ☐ Right	***If bilateral, complete ONE form PER SIDE*** Bilateral: ☐ Left ☐ Right
Type of Replacement	***Check ONE only*** ☐ Primary ☐ Revision	
Type of Primary Procedure	***Check ONE only*** ☐ Total knee arthroplasty (TKA), including patella ☐ Total knee arthroplasty (TKA), excluding patella ☐ Unicompartmental arthroplasty (UKA), medial	☐ Unicompartmental arthroplasty (UKA), lateral ☐ Patellofemoral arthroplasty (PFA) ☐ Other
Diagnosis Grouping (for Primary Procedure Only)	***Check MOST RESPONSIBLE diagnosis for involved knee (check ONE only)*** ☐ Degenerative arthritis (e.g. OA) ☐ Inflammatory arthritis (e.g. RA, AS, SLE) ☐ Osteonecrosis (e.g. AVN) ☐ Infection	☐ Tumour (primary and metastatic, including synovial) ☐ Fracture (femur or tibia) ☐ Other
Reason for Revision (for Revision Procedure Only)	***Check MOST RESPONSIBLE reason for revision to involved knee (check ONE only)*** ☐ Aseptic loosening ☐ Bearing wear (e.g. poly wear) ☐ Osteolysis ☐ Instability (e.g. dislocation, excludes patella instability) ☐ Infection—single-stage revision ☐ Infection—stage 1 of two-stage revision ☐ Infection—stage 2 of two-stage revision	☐ Pain of unknown origin ☐ Patella maltracking or instability ☐ Peri-prosthetic fracture (femur or tibia) ☐ Implant fracture (any component) ☐ Implant dissociation (e.g. stem from tibial tray) ☐ Arthritis in previously unresurfaced compartment (e.g. patellofemoral, medial or lateral compartment) ☐ Stiffness ☐ Other

Sticker(s) for Femoral Component

Sticker(s) for Tibial Component (Including "All Poly" Tibias)

Sticker(s) for Tibial Insert

Sticker(s) for Patellar Component

Sticker(s) for Cement

DO NOT FAX OR MAIL FORMS. Contact CJRR at cjrr@cihi.ca or 416-481-2002.

Formulaire disponible en français

Appendix B

Data Quality and the Implant Reference Library: Supplementary Material

This appendix contains supplementary material for Chapter 2. Numbered citations refer to the reference list at the end of that chapter.

B.1 CJRR Data Collection and Reporting

B.1.1 CJRR Data Submission

The CJRR has defined a minimum data set to collect the relevant clinical, surgical, and prosthesis information for knee and hip replacements [18]. As outlined in their Minimum Dataset Manual [18], the definitions and specifications of each required field are presented, including the field length, field status (mandatory or optional), valid data, and the relevant joint types for each field. The required fields include patient information such as age, date of birth, sex, and health card information; surgical elements such as surgery date, hospital ID, surgeon ID, province, type of replacement, and prosthesis information, including component types, product numbers, lot numbers, and manufacturers.

As of 2025, there are 3 main pathways for data submission to the CJRR: the legacy CJRR electronic file system, the Discharge Abstract Database (DAD) which generally captures inpatient hospitalizations, and the National Ambulatory Care Reporting System (NACRS), which covers ambulatory care, emergency, and same-day surgeries [23]. Previously, the CJRR also accepted submissions via paper forms and a web tool; however, these methods have since been retired in favour of electronic file submission due to reduced manual data entry and improved integration with existing hospital systems [1,23].

Using the legacy CJRR electronic file system, record-level data is captured using an approved software through CIHI's electronic Data Submission Services (eDSS) or a server-to-server (SFTP) application and submitted to CIHI as flat ASCII files directly from the data provider (e.g., hospital, vendor, health authority) [24,25]. The submissions are then processed and assessed for validity and data quality. The automatic validation checks include flagging errors against the criteria outlined in Appendix E of the CJRR Minimum Data Set Manual, such as blank fields, invalid field lengths, and out-of-range values, and rejecting the record if the criterion is not met [18]. A report is then generated and sent back to the data provider outlining how many records were successfully submitted and why other records were rejected, allowing the data provider to correct the errors and resubmit. Accepted records are then de-identified and uploaded to the CIHI analytical environment for analysis [25].

Similar data flows are used for submissions via the DAD or NACRS. Hospitals are required to regularly submit DAD and NACRS abstracts to CIHI, which holds both databases. Thus, the required CJRR fields, such as prosthesis information, are embedded in these reports and submitted to the CIHI. The internal CIHI systems then extract the CJRR fields and run validation checks before uploading them into the CJRR (same as the legacy CJRR submission) [26].

The particulars of data entry for any of these submission streams may differ depending on the software used by the submitting facility. CIHI requires that software vendors pass testing before approval for data submission. One of the approved software vendors for CJRR data submission is MED2020 Healthcare Software Inc., for its WinRecs 3.0 software, a modular health information management tool that captures and reports medical data

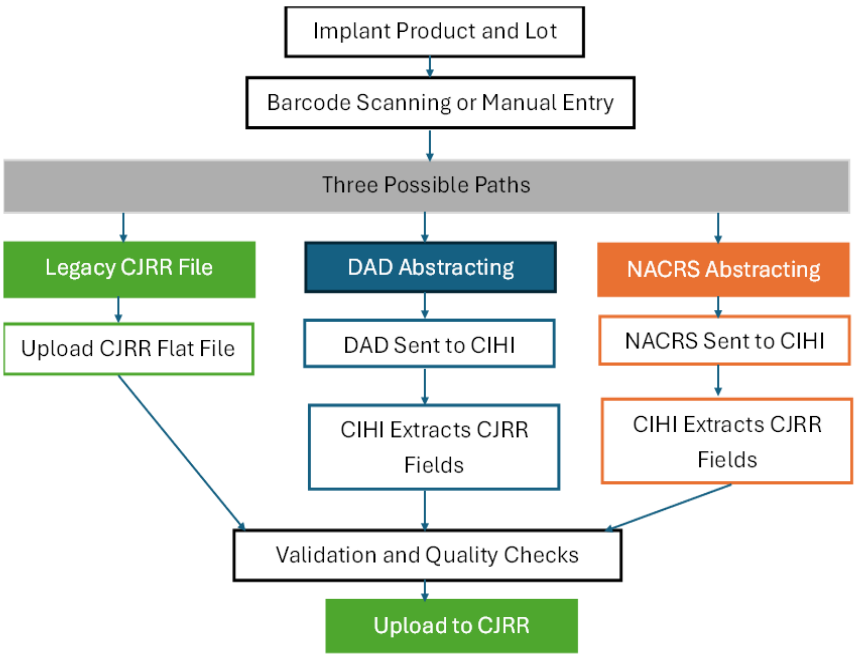


Figure B.1: CJRR data submission pathways and data sources.

[19,24]. In WinRecs 3.0, CJRR records can be submitted directly via the CJRR module (manual creation), through DAD/NACRS abstracting, or via batch interfacing from an operating room (OR) system.

For manual record creation, the surgeon or facility staff must create a new record, select the joint and type of replacement, and link the record to a patient chart. The software then automatically populates any common elements between the central patient index (CPI) and the CJRR form. Other required fields, such as product number, lot number, and manufacturer, must be entered for each component type used (e.g. for knee replacements: patellar, femoral, or tibial); otherwise, error messages will be displayed. There are two options for entering the prosthesis or cement information: manual entry or barcode scanning. There are typically two barcodes on the packaging for each prosthesis component and cement, which can be scanned into the product number and lot number fields of the CJRR form. The CJRR recommends this over manual entry to reduce transcription errors [18].

If abstracting through DAD or NACRS, one of the following Canadian Classification of Intervention (CCI) codes must be present to trigger the CJRR form: 1.VA.53.XX (implantation of internal device, hip joint), 1.SQ.53.XX (implantation of device, pelvis), 1.VG.53.XX, (implantation of device, knee joint), 1.VP.53.XX (implantation of device, patella) [19,27]. The surgeon or abstractor must then manually or via barcode scanning fill the prosthesis information fields (component type, product number, lot number, manufacturer), as the required patient and hospital information is already present in the DAD/NACRS record (Fig. B.2). If using batch interfacing, the OR system-generated file can be loaded into the WinRecs application, then submitted to CIHI. Before successful submission to CIHI, all abstracts are validated to ensure none of them have outstanding errors. If error messages exist in any of the files, they must be corrected before submission to be successful.

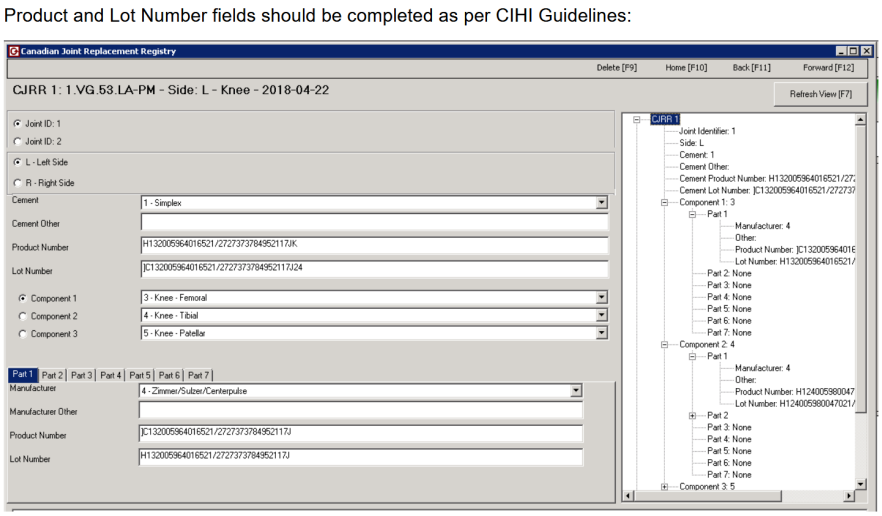


Figure B.2: WinRecs 3.0 CJRR Data Entry

After receiving the submissions, the CIHI links the records to relevant databases, such as the International Product Library (IPL), to fill prosthesis brand information fields [1,28,29]. The product numbers submitted to CJRR are typically either in Global Trade Item Number (GTIN) or Health Industry Bar Code (HBIC) format. Those submitted as GTINs are mapped to their corresponding HBIC numbers, which are subsequently linked to the IPL.

B.1.2 Data Coverage and Variability

While CJRR data submission is not mandatory across Canada, several provinces have implemented mandatory submission (Table B.1). Since 2012, Ontario, Manitoba, and British Columbia have mandated CJRR submissions, while Nova Scotia implemented the requirement in 2018 [1]. With Ontario conducting the majority of all replacement procedures in Canada (based on 2023-2024 data), approximately 45%, and British Columbia responsible for the second greatest procedure volume at 13% (tied with Quebec), nearly 60% of all replacement procedures in Canada are mandatorily reported. Even in many voluntary-submission jurisdictions, including Saskatchewan, Newfoundland and Labrador, and the Northwest Territories, reporting rates have been greater than 90% (since 2018). However,

other provinces such as Quebec exhibit drastically lower reporting rates, ranging from 0.5% to 2.3% since 2018 [23]. Considering this, the overall national reporting rate has, not surprisingly, averaged only 73% since 2018 [23]. The CJRR explicitly reports that low reporting rates are a potential source of bias in analysis, as jurisdictions with low coverage may differ significantly from those with greater coverage [28]. Thus, they recommend limiting analyses to jurisdictions with high coverage.

Table B.1: CJRR percentage coverage by jurisdiction, 2019-2023 (Canadian Institute for Health Information, 2023, 2026).

Jurisdiction	**2019**	**2020**	**2021**	**2022**	**2023**
Newfoundland and Labrador	99.6	99.0	99.0	98.8	99.4
Prince Edward Island	n/a	n/a	n/a	n/a	n/a
Nova Scotia*	94.8	93.8	92.9	94.6	94.4
New Brunswick	10.4	8.1	11.0	8.3	6.5
Quebec	1.9	0.4	0.6	2.3	2.2
Ontario*	95.8	91.8	84.8	91.9	93.8
Manitoba*	99.7	99.8	99.2	99.6	99.4
Saskatchewan	90.0	90.6	99.6	99.9	99.8
Alberta	80.8	76.3	74.7	72.4	74.2
British Columbia*	88.4	97.2	95.6	95.0	86.9
Yukon	n/a	n/a	n/a	n/a	n/a
Northwest Territories	97.8	98.6	98.5	90.2	100.0
Canada	**73.4**	**73.9**	**68.2**	**72.4**	**72.1**

* Provinces with mandatory CJRR submission.

B.1.3 Current Quality Assurance Practices and their Limitations

The CIHI implements various data quality checks before data submission and during processing; however, they still report issues with missing or miscoded variables [1]. As outlined in the CJRR Minimum Data Set Manual and WinRecs 3.0 guide, mandatory fields with missing entries or values outside of allowable ranges are flagged as errors and cannot be submitted until corrected. More specifically, the field inputs are assessed for allowable lengths and character types, as well as for empty or missing fields. However, these measures do not ensure that the entered values are necessarily legitimate or correspond to the relevant variable definition. For example, a product entered as long as it is within the 60-character limit will be accepted, even if it does not correspond to any prosthesis component in the database and would subsequently cause issues when attempting data linkage to the IPL, resulting in missing data for this entry. Similarly, there are no real-time logic checks to confirm that the product number corresponds to an implant of the specified component type, which could lead to data misclassification. However, some CJRR forms, such as those completed in the WinRecs module, include drop-down menus for selecting component manufacturers, reducing manual data entry and promoting standardized variable options. Moreover, while barcode scanning reduces errors in product and lot number transcription, there is also a risk of scanning the barcode into the wrong field or into both the product and lot number fields, for which there is no documented validation check. While the entered product numbers are cleaned and linked to the IPL, no validation or logic tests are performed using the IPL prosthesis information, such as cross-checking that the component type entered in CJRR for each product number matches the IPL-provided component type, leaving room for component misclassification.

B.1.4 International Registry Context

In contrast to the CJRR, large international registries, including the Australian Orthopedics Association National Joint Replacement Registry (AOANJRR), the Dutch Arthroplasty Register (LROI), and the National (British) Joint Registry (NJR), have progressed towards greater quality assurance and quality control measures such as mandated data cap-

ture, active linkage-based validation, and structured data auditing programs [13–16]. The outcomes of such data quality measures are evident, for example, the Australian registry achieves extremely high national coverage (approximately 99% of knee, hip, and shoulder replacements) through mandated nationwide participation. Moreover, the AOANJRR reports high data completeness, attributed to its systematic cross-checking of registry data with hospital and health department sources. In addition to correcting data errors through cross-checking, the Australian registry also implements real-time checks and features such as predictive text in data entry to reduce errors and identify discrepancies in the data, which are followed up with the hospitals and resolved [13,14].

The Dutch registry, like the CJRR, uses barcode scanning and an associated implant library which automatically pulls prosthesis information to reduce manual data entry errors. However, in addition, the LROI validates the implant characteristics against manufacturer product information before linkage to the implant library to flag unknown product numbers, which are reconciled by the hospitals and manufacturers. The feedback loop of validation of data-entry variables and follow-up with the hospitals not only corrects data but has also revealed common misclassification errors, allowing correction of variable coding ambiguities [15].

The British registry implements large-scale data quality audits, cross-referencing NJR records with hospital patient administration systems to identify missing or unmatched procedures. Since its implementation, the bidirectional validation has improved reporting rates, data completeness, and confidence in registry estimates [16].

The CJRR public documentation emphasizes general edit checks and record-level error reporting to data providers but provides little detail on systematic, publicly reported audit cycles comparing CJRR data with external sources, or active, recurrent feedback on data errors and misclassifications. Adaptation of some of the above elements, such as systematic external validation, comprehensive mandated coverage, enhanced feedback and follow-up with data providers, and thorough data quality audits, could substantially strengthen the CJRR's data quality framework.

B.2 CJRR Data Challenges

B.2.1 Variable Coding and Data Definition Inconsistencies

In addition to the variables outlined in the CJRR Minimum Data Set, numerous other variables obtained through data linkages within CIHI are available for analyses of CJRR data. For example, implant prosthesis information from the IPL, including size and surface material, as well as hospital classifications from CIHI's Organization Index, such as teaching versus community hospitals, is available. However, inconsistencies in variable coding and definitions have resulted in questionable data reliability.

For example, in CIHI's Indicator Library, hospitals are categorized into one of four "standard peer groups": T (teaching), H1 (Community – Large), H2 (Community – Medium), or H3 (Community – Small). Teaching hospitals are defined as those with confirmed teaching status from the provincial ministry or identified as teaching in the provincial ministry's submission to the Canadian MIS Database [30]. However, this does not necessarily capture all facilities with teaching programs or medical program affiliations. Even with an accredited residency program and membership in the Association of Canadian Academic Healthcare Organizations (ACAHO), some hospitals are not classified as teaching hospitals according to the CIHI definition [30]. One example of this situation occurs in Manitoba. Despite provincial requirements for submission, CJRR reports no total knee replacements at teaching hospitals from 2019 to 2023, even though there is a well-known orthopedic residency program affiliated with the University of Manitoba at Concordia Hospital in Winnipeg, a major population centre in Manitoba [30–32]. The discrepancy seems to arise in the provincial ministry documentation of the hospital; the Winnipeg Regional Health Authority (WRHA) documentation has previously listed Concordia as a "community hospital," aligning with CIHI's H1 community-large grouping [30,33]. Thus, to be classified as a teaching hospital by CIHI, corrections by the health ministry to designate it as such in the official institutional and MIS submissions must be taken. However, until corrective actions are taken, this could result in misrepresentation of the hospital landscape and inaccurate comparisons of replacement trends across hospital types.

Additional issues with variable definitions are even present in implant brand information fields from the IPL, such as model and product name. According to the CJRR/IPL, the product name is defined as "the trademarked name of the component and usually appears on the component label," whereas the model name "can be created only using the company trademark name or incorporating attributes such as fixation, stability, mobility, material with the trademark name." These definitions are somewhat vague and have led to inconsistent naming conventions, with variations in capitalization, hyphenation, and attribute information for the same model. While the CJRR documentation explicitly acknowledges that product labelling is not standardized across or even within manufacturers, clarifying variable definitions and imposing formatting rules promoting standardized model and product names would greatly improve the usability of such fields [18,21].

Similarly, standardization of joint component labels would improve component classification. Currently, there are numerous variations of the same component names within the joint component field (e.g. Knee-Femoral, Femoral Component). This may be due to variations of the component labels in the software used for DAD/NACRS abstracting and CJRR form completion. The WinRecs 3.0 software displays "Knee-Femoral, Knee-Tibial", and "Knee-Patellar" as component labels; however, other approved software may differ [24,34]. Nevertheless, imposing registry-level naming standards would improve the usability of the CJRR data.

B.2.2 Integration Across Multiple Reporting Systems

While allowing multiple data submission streams to the CJRR (legacy CJRR, DAD, NACRS) (Fig. B.1), may improve integration with existing hospital documentation workflows, discrepancies arising from combining submissions from different systems can introduce data quality issues. Approximately half of all CJRR submissions are from DAD and NACRS, which include CCI codes to indicate procedure features. However, the legacy CJRR submissions do not include this, and thus, such fields obtained from the CCI codes, including primary intervention code, status attribute, location attribute, and the CCI cement flag, are not populated. While such information is often available in similar fields, the

additional information provided by CCI codes enables further verification and enhanced data reliability.

B.2.3 Data Source Composition

The dataset comprises 230,949 records, submitted across three reporting streams: the legacy CJRR system (122,956 records; 53.2%), the Discharge Abstract Database (100,489 records; 43.5%), and the National Ambulatory Care Reporting System (7,504 records; 3.2%). Submission source varied substantially by province. British Columbia, Manitoba, Newfoundland and Labrador, Nova Scotia, the Northwest Territories, and Saskatchewan submitted exclusively through a single source, while Alberta and Ontario used a mix. Ontario, which contributes the largest volume of records, drew approximately 43% from legacy CJRR, 51% from DAD, and 6% from NACRS. Alberta split submissions roughly 65% CJRR and 35% DAD (Fig. B.3).

B.2.4 Missingness by Data Source

Field-level missingness differed markedly across submission streams (Fig. B.4). All CJRR submission streams showed near-complete capture of fields such as REPLACEMENT_TYPE, REPLACEMENT_SIDE, AGE_SURGERY, FISCAL_YEAR, and GENDER. However, the CJRR legacy stream had systematic missingness in fields derived from CCI codes, including PRIMARY_PROC_TYPE, STATUS_ATTRIBUTE_CODE, LOCATION_-ATTRIBUTE_CODE, and EXTENT_ATTRIBUTE_CODE, as the legacy stream does not collect CCI codes. Conversely, DAD and NACRS submissions populated these CCI-derived fields as they are abstracted from the EMR but had increased missingness in several implant characteristic fields such as Stability, Fixation, MMat, PMat, and Mobility. However, these fields are IPL-derived, suggesting an IPL deficiency for the catalogue numbers submitted through DAD/NACRS rather than a data submission issue. However, if the submitted catalogue numbers were invalid, the same effect would occur as linkage to the IPL would be hindered. Fields relating to implant surface treatment

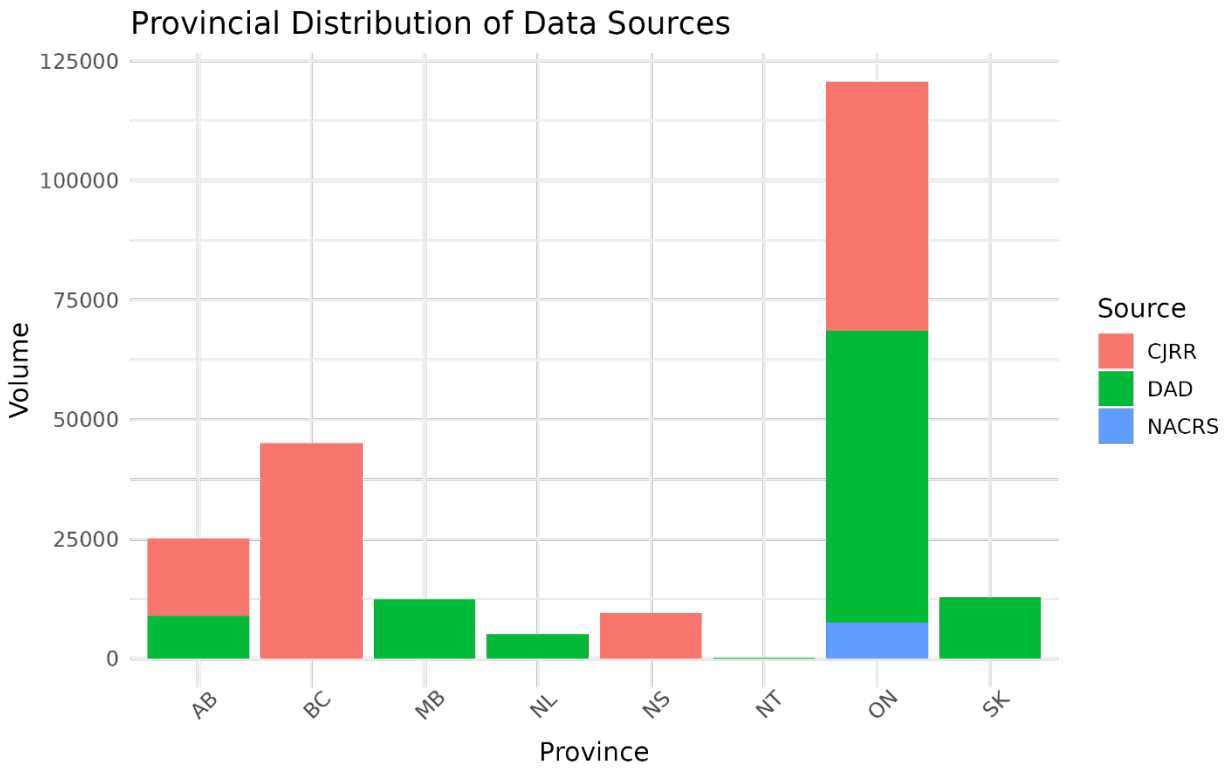


Figure B.3: Provincial distribution of data submission streams.

(Surf_TreatmentFixationSurf, Surf_TreatmentBearSurf) and component design were consistently missing across all three sources, underscoring that the primary driver of missingness for these variables is incomplete implant library linkage rather than submission pathway.

B.2.5 IPL Field Missingness by Component Type

Missingness in implant-level fields also varied substantially by joint component type (Fig. B.5). Across the four primary component types, Femoral, Insert, Patella, and Tibial, core identifiers (JOINT_ID, JOINT_COMP, CATALOGUE_NUM_CLEANED, MANUFACTURER_NAME_STD) were well-populated. However, implant characteristic fields had high missingness, particularly for clinically relevant attributes (material, dimensions, mobility, etc.). Though, it should be noted that not all descriptive fields are applicable to all component types. For example, polyethylene inserts will not have metal material (MMAT) or ceramic material (CMMat) fields, and femoral components will not have an insert thickness (Thick) field.

For femoral components, relevant fields such as FixationSurfaceCementless, DesignArticularSurface, DesignFixationSurface, and FlexionCapacity were missing in a substantial proportion of records. Patella components showed the most uniformly poor coverage across descriptive fields, with many attributes approaching 100% missingness, consistent with their limited representation in the IPL. Insert components exhibited high missingness for Thick (thickness), TotalSide, and UDI, while tibial components showed notable missingness for AP dimension, ML dimension, and surface treatment fields. These patterns reflect both the limits of catalogue number linkage and the sparseness of certain IPL fields for specific component types.

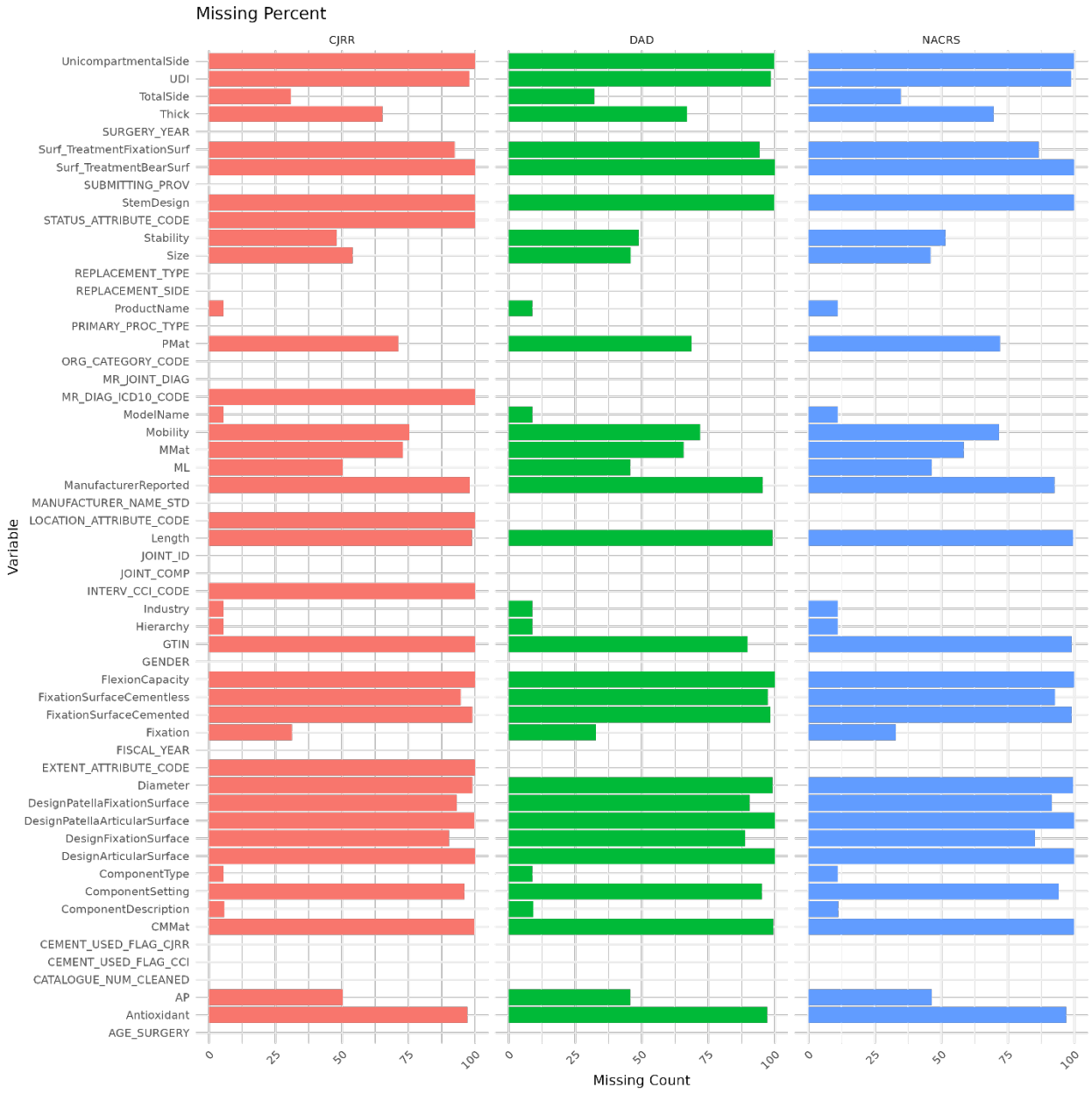


Figure B.4: Variable missingness (%) by data source.

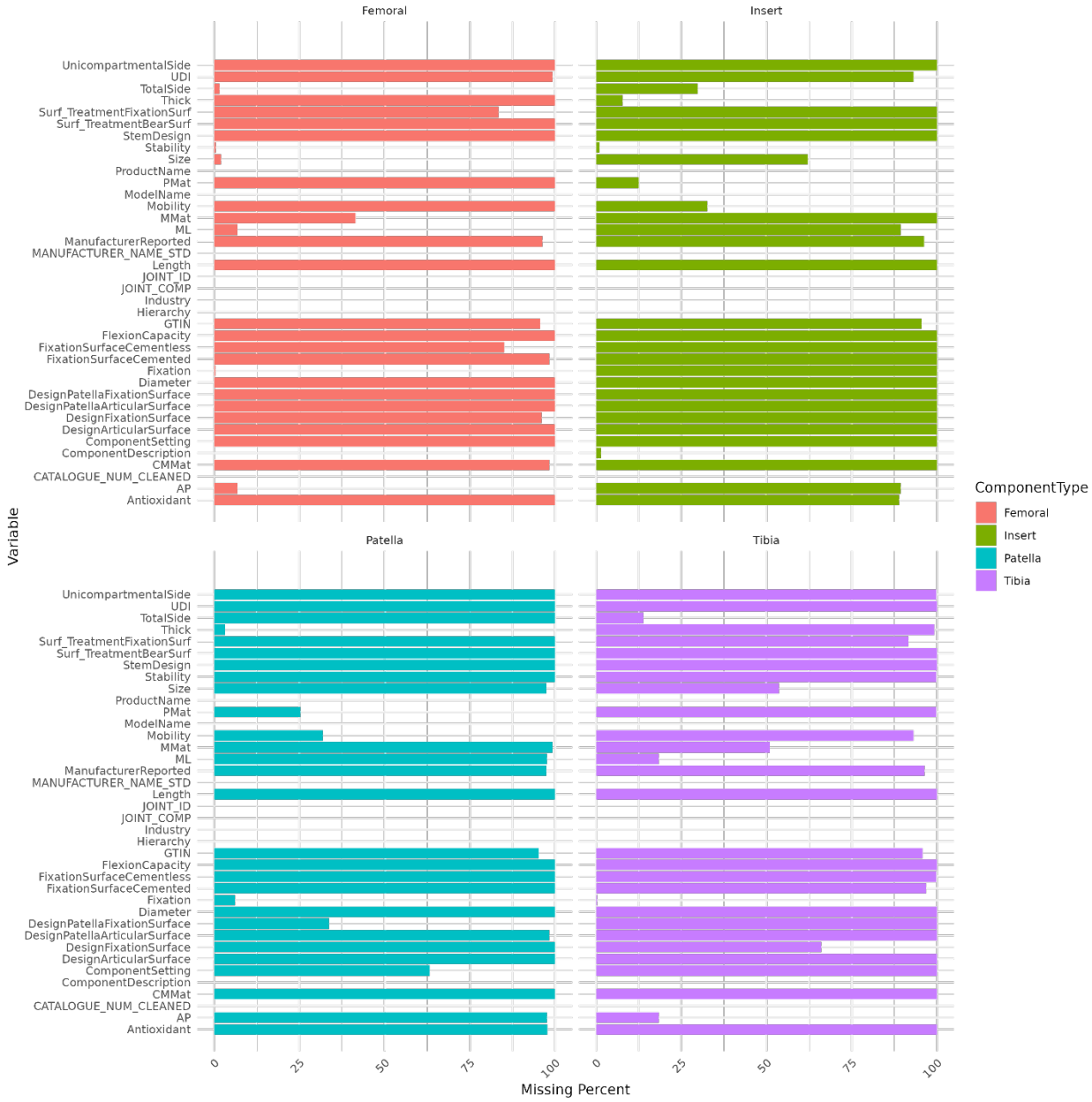


Figure B.5: Variable missingness by component.

B.2.6 Variable Disagreement

JOINT_COMP and ComponentType

The JOINT_COMP field, entered by submitters to classify each component, exhibited systematic mismatches with the ComponentType field derived from the IPL. A congruency analysis between the submitter-entered JOINT_COMP field and the IPL-derived ComponentType field showed high but incomplete agreement for femoral (93.6% congruent, 4.0% unmatched) and patellar (95.4% congruent, 3.6% unmatched) components, and substantially lower agreement for tibial components: JOINT_COMP entries labelled "Tibial Component" corresponded to a tibial baseplate ComponentType in only 65.6% of cases (24.6% instead matched a knee insert ComponentType, and 7.8% had no matched ComponentType), and entries labelled "Tibial Poly Insert" corresponded to a knee insert ComponentType in 85.4% of cases but were unmatched in 14.1%. These mismatches may indicate barcode scanning errors or incorrect field entry and suggest that submitter-selected JOINT_COMP labels cannot be taken at face value without cross-referencing the IPL-derived component type.

Manufacturer and ModelName

A related but distinct issue was identified within the CJRR/IPL-linked data regarding the manufacturer field (MANUFACTURER_NAME_STD). Each catalogue number should correspond to a single manufacturer and model, however, a total of 705 unique catalogue numbers were associated with more than one manufacturer/model-name combination, and 666 catalogue numbers were associated with more than one manufacturer outright. This pattern suggests potential data entry errors at the point of CJRR submission. For example, an incorrect manufacturer selected during manual entry (as described in the WinRecs workflow in Section B.1.1), or a barcode scanned against the wrong product record, rather than a limitation of the IPL. However, this still poses additional challenges to users aiming to conduct model or manufacturer level analyses, as the reported labels may not be reliable.

B.2.7 Duplicate Component Types

A related issue is the presence of duplicate component types within the same joint record. Each complete joint record should have a maximum of 1 of each component type (femoral, tibial baseplate, tibial insert, patella, stem). Across the dataset, 3,647 JOINT_IDs contained duplicate Insert entries, 1,005 had duplicate Tibia entries, 707 had duplicate Femoral entries, and 144 had duplicate Patella entries. An additional 7,787 JOINT_IDs had component entries with a null component type (NA), making it challenging to classify the duplication pattern without further investigation. These duplicates may reflect barcode scanning of both the component and packaging label into separate rows, data entry errors, or revision components recorded within the same joint record.

B.2.8 Component Completeness

Of 230,922 joint records with at least one component entry, 189,478 (82.1%) had a complete component set, defined as the presence of femoral, tibial, and insert components, or femoral and monoblock tibial components. The remaining 41,444 records (17.9%) were missing at least one expected component, reducing their suitability for inclusion in analyses requiring complete implant systems.

B.2.9 Unmapped Catalogue Numbers

Incomplete catalogue number linkage to the IPL can be attributed to various factors, including the absence of a valid catalogue number from the IPL or invalid catalogue number submission (typos, scanning errors). Overall, 7.1% of unique catalogue numbers had no corresponding IPL information, affecting 56,560 component-level rows and 44,169 unique joint records. Missingness was concentrated in certain manufacturers: several smaller manufacturers (Ceraver, Corin, Medacta International) had 100% unmapped catalogue numbers, and Link showed 93% unmapped. Among higher-volume manufacturers, Stryker/Osteonics/Howmedica had 11.3% of its records unmapped, DePuy/Finsbury/J&J

had 9.8%, and Zimmer/Biomet/Sulzer/Centerpulse had 4.4%. Notably, only 2.6% of unmapped catalogue numbers were identifiable as substrings of UDIs in the IPL, suggesting these are not simply formatting discrepancies but reflect true gaps in the reference library.

The various data sources for the CJRR showed similar trends in unmapped catalogue number submissions (Fig. B.5). Both CJRR Legacy and DAD submission streams had increased unmapped rates from 2019-2023. NACRS, however, only had data from 2022-2023, yet still showed an increase in unmapped catalogue number submissions.

Unmapped catalogue number rates also varied substantially by province (Table B.2). Newfoundland and Labrador had the highest proportion of unmapped catalogue numbers, followed by Nova Scotia and Ontario. In contrast, Manitoba, Saskatchewan, and the Northwest Territories showed comparatively low unmapped rates. A chi-squared test confirmed that these provincial differences were statistically significant (χ^2=8250.1, df=7, p<0.001), consistent with systematic differences in submitting facility software, barcode scanning practices, manufacturer/procurement contracts, or data entry workflows across jurisdictions.

Table B.2: Provincial distribution of unmapped catalogue numbers form 2019-2023

Province	**Percent Unmapped (%)**
Alberta	17.8
British Columbia	13.1
Manitoba	4.1
Newfoundland & Labrador	40.1
Nova Scotia	26.9
Northwest Territories	7.6
Ontario	23.3
Saskatchewan	3.5

Temporal trends in unmapped catalogue numbers further illustrate the scope of the

issue (Figs. B.6 and B.7). The cumulative volume of unmapped catalogue numbers increased steadily across all provinces from 2019 to 2023, with Newfoundland & Labrador contributing the largest absolute percent increase (64%). Fig. B.6 shows that growth in unmapped records was not uniform: provinces such as Newfoundland, British Columbia, and Saskatchewan had accelerating accumulation in later fiscal years, suggesting that either new implants were introduced without corresponding IPL entries, or perhaps that data entry practices slackened over time.

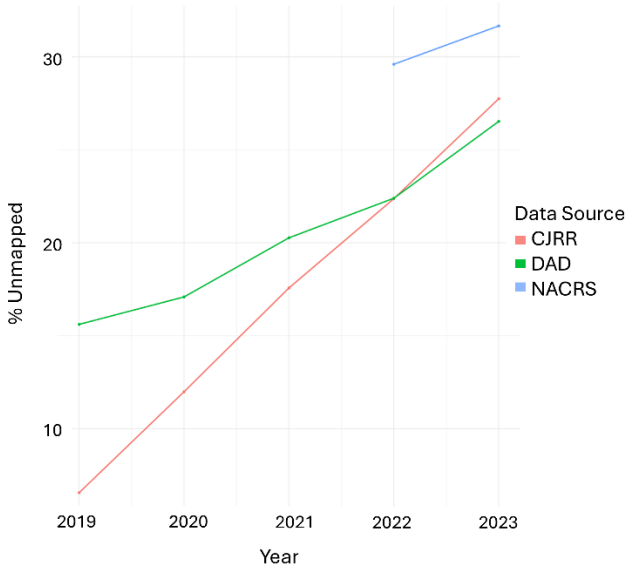


Figure B.6: Unmapped catalogue number submission rates over fiscal years by data source.

B.3 Implant Library Development Technical Details

B.3.1 Rationale

The data quality issues described above collectively limit the ability to conduct, and reliability of implant-level analyses from CJRR data. While the IPL provides linkage between

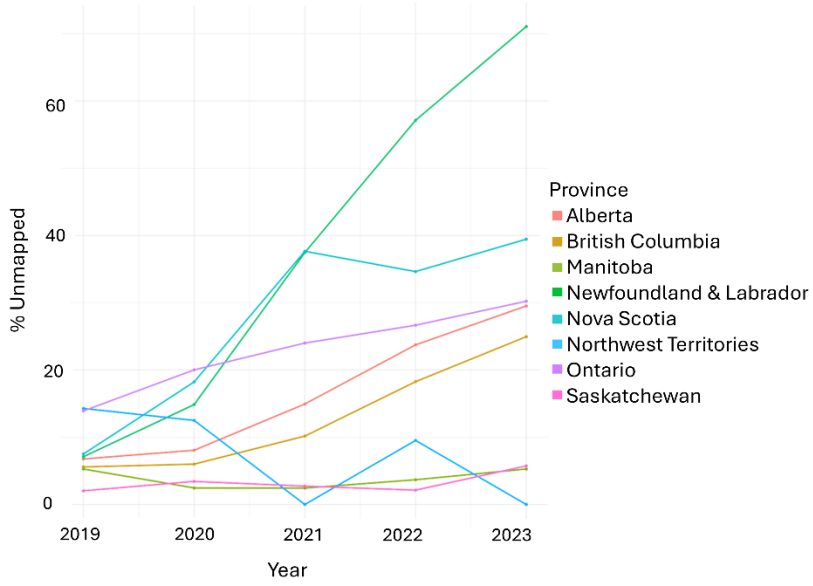


Figure B.7: Provincial rates of unmapped catalogue number submission by fiscal year. (Alberta (n = 25,174), British Columbia (n = 45,112), Manitoba (n = 12,377), Newfoundland & Labrador (n = 5,083), Nova Scotia (n = 9,532), Northwest Territories (n = 158), Ontario (n = 120,626), Saskatchewan (n = 12,887)).

submitted catalogue numbers and implant brand information, it is not publicly accessible, its coverage is incomplete, and it lacks transparency regarding the provenance and validation of its fields. Researchers working with CJRR data therefore have limited ability to verify, correct, or supplement the implant information they receive.

To address these gaps, an open-source implant reference library was developed for Canadian TKA devices. The library serves to provide a comprehensive, structured source of implant identifiers and device characteristics that can be used to validate and supplement registry data, enabling cross-referencing of submitted catalogue numbers, component type verification, and filling of missing implant characteristic fields. It also adds transparency regarding data sourcing: each record includes a data_source field indicating which upstream databases and documents contributed to its content, and a per-field field_status indicating whether each attribute is populated, missing, or not applicable for that component type. This supports reproducibility and allows users to assess the reliability of any given field for their specific research question. Moreover, the library is designed to be maintainable and extensible, with a modular pipeline that can be re-run as new devices enter the market or regulatory databases are updated, without requiring access to proprietary registry infrastructure.

B.3.2 Data Sources for the Reference Library

The library was constructed by integrating data from multiple regulatory and manufacturer sources.

The FDA Global Unique Device Identification Database (GUDID), maintained by the U.S. Food and Drug Administration, provides standardized device identification records for all medical devices marketed in the United States, including Canadian-market knee implants sold by international manufacturers [35,36]. Device records include the Global Trade Item Number (GTIN), catalogue number (VERSION_MODEL_NUMBER), brand name, company name, FDA product code, and Global Medical Device Nomenclature (GMDN) term [36,37]. Bulk downloads were obtained for knee implant-relevant FDA product codes (e.g. JWH, MBH), and per-device descriptions and size annotations were additionally re-

trieved via the GUDID REST API (endpoint: accessgudid.nlm.nih.gov/api/v3/devices /lookup.json), which provides richer free-text device descriptions than the bulk download alone.

The Health Canada Medical Devices Active Licence Listing (MDALL), contains records of all medical devices licensed for sale in Canada, including the licence number, device name, and manufacturer [38]. Unlike GUDID, MDALL device names frequently encode clinically relevant attributes such as stability type (CR/PS), fixation, and component designation directly in the device name field, providing a complementary source of characteristic information not always present in GUDID records. Bulk downloads were obtained for knee implant search terms.

Global Medical Device Nomenclature (GMDN) terms, which provide standardized names, codes, and definitions to identify medical devices [37], were also used to identify relevant records from the FDA GUDID, as it includes GMDN terms for its listed devices.

Electronic Instructions for Use (eIFU) PDFs were also utilized. For implant systems where regulatory database records lacked material composition data, eIFU PDFs were obtained from manufacturer portals using automated browser-based downloading (via Selenium). Material composition information, including metal alloy specifications, polyethylene type, and antioxidant additives, was extracted from the PDFs using manufacturer-specific text parsers, as the formatting of material tables differs substantially across manufacturers.

Two supplemental reference files were used for dimensional enrichment: a procedure-level records file covering Zimmer NexGen and Persona systems sourced from Ortech, and a compiled dimension lookup table covering Stryker, DePuy, Smith & Nephew, and Zimmer/Biomet systems across femoral, tibial, and insert components manually sourced from manufacturer documentation. These provided AP depth, ML width, insert thickness, and diameter data that are not systematically captured in regulatory databases.

A supplemental CSV of New Zealand-registered medical devices [39] that was publicly released via an Official Information Act request was also incorporated to improve coverage for catalogue numbers present in the Canadian market but absent or incomplete in GUDID and MDALL.

For records that could not be auto-populated from any of the above sources, an optional, structured manual review workflow was devised. The pipeline generates a grouped needs_review output file with one row per manufacturer/brand/component type combination, pre-populated with any fields already consistent across all catalogue numbers in the group, with remaining fields left blank for manual completion. Completed review files can then be applied back to the library via a separate validation script.

B.3.3 Data Elements Included

The library contains one row per catalogue number. Fields are grouped into five categories: identifiers, basic information, component classification, design characteristics, and dimensional attributes.

Identifiers include the catalogue number (primary key), GTIN, Health Canada MDALL licence number, MDALL internal device identifier, and FDA device identifier (DI). These support linkage to the CJRR submitted catalogue number and GTIN fields and enable cross-referencing with both Canadian and American regulatory databases.

Basic information includes brand name, manufacturer (mapped to CJRR canonical names), FDA product code and product code description, GMDN term, and free-text device description from the GUDID API. The raw MDALL device name is also retained separately, as it frequently contains richer characteristic information than the GUDID brand name.

Component classification assigns each record a component_type (Femoral, Tibial, Insert, Patellar, TKA System, Femoral Stem, Tibial Stem, or Stem) derived from the GMDN term, and a replacement_type (Primary or Revision).

Design characteristics encode the clinically relevant implant attributes most commonly used in registry analyses. These are described in Table B.3 with their applicable component types, as many fields are structurally inapplicable to certain components, for example, mobility (Fixed Bearing, Mobile Bearing, Rotating Platform) applies only to insert components, while fixation (Cemented, Cementless, Hybrid) applies to femoral and tibial com-

ponents but not to inserts, which are press-fit into the tibial tray. The stability field (CR, PS, CPS, BCS, Semi-Constrained, Constrained) applies to femoral components and inserts but not to tibial baseplates or patellar components, as it describes the constraint philosophy of the articulating pair rather than the baseplate itself. Material fields are similarly scoped: metal_material (CoCr, Titanium, Oxidized Zirconium) applies to femoral, tibial, and patellar components, while poly_material (UHMWPE, XLPE, UHMWPE+VitE, XLPE+VitE) applies to insert and patellar components. The antioxidant field flags the presence of Vitamin E stabilization and is populated for any record where poly_material contains an antioxidant designation.

Dimensional attributes include anteroposterior (AP) length (medial and lateral separately for asymmetric components), mediolateral (ML) width (Fig. B.8), insert thickness, and stem/patellar diameter, each scoped to the component types for which the dimension is meaningful (Table B.3).

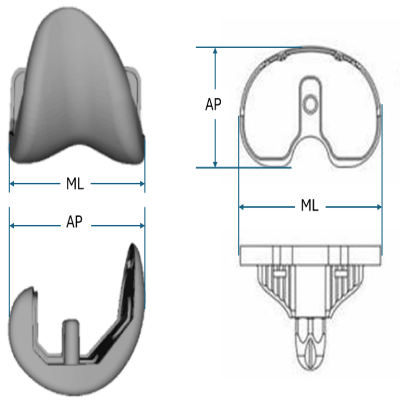


Figure B.8: Femoral and tibial component anteroposterior (AP) and mediolateral (ML) dimensions.

Table B.3: Open-source implant reference library field applicability matrix.

Field	Applicable Component Types	Not Applicable
stability	Femoral, Insert, TKA System	Tibial, Patellar, Stem
mobility	Insert	All others
fixation	Femoral, Tibial, TKA System	Insert, Patellar, Stem
design_fixation_surface	Femoral, Tibial, Patellar	Insert, Stem
design_articular_surface	Femoral, Insert	Tibial, Patellar, Stem
ap_length (medial and lateral)	Femoral, Tibial	Insert, Patellar, Stem
ml_width	Tibial	All others
diameter	Patellar, Femoral Stem, Tibial Stem, Stem	Femoral, Tibial, Insert
thickness	Insert	All others
metal_material	Femoral, Tibial, Patellar	Insert, Stem
poly_material	Insert, Patellar	Femoral, Tibial, Stem
antioxidant	Insert	All others
surface_treatment	Femoral, Tibial	Insert, Patellar, Stem

This applicability matrix (Table B.3) is applied programmatically during pipeline construction. Fields marked not applicable are assigned a field_status of not_applicable rather than missing, ensuring that apparent missingness in summary statistics is not inflated by fields that are structurally inapplicable to a given component type.

Each record additionally carries metadata fields: data_source (a list of contributing

sources), match_type (exact, normalized, or unmatched for GUDID-MDALL linkage), confidence_score (the fraction of applicable fields populated, ranging 0-1), needs_review (flagged if any applicable field remains missing), and notes for free-text annotations.

B.3.4 Construction and Validation Procedures

The library was built through an eleven-stage pipeline (Section B.3), implemented in Python and designed to be re-executable from any intermediate checkpoint.

1. GUDID bulk download and instrument exclusion

   Device records were downloaded in bulk from the FDA GUDID for all knee implant-relevant product codes. A GMDN-based keyword exclusion filter was applied to remove non-implant device records, including surgical instruments (e.g. drill bits, reamers, broaches), implant trials, revision hardware extensions (augments, wedges), and non-knee implants, which were present in the GUDID under the same product codes as implants but would inflate the library with non-applicable records. The exclusion filter was re-applied as a safety net at any pipeline entry point that bypasses the download stage (e.g. using a pre-existing download file).

2. MDALL bulk download

   Device records were downloaded from Health Canada's MDALL database using knee implant search terms. The downloaded file was then filtered on device name to exclude non-knee implant devices using a regular expression (regex) keyword exclusion filter.

3. Merge

GUDID and MDALL records were merged on catalogue number (VERSION_MODEL_NUMBER) using a two-pass strategy: exact string match after uppercase normalization and whitespace stripping, followed by a normalized match after additionally removing hyphens and spaces. Records were classified as BOTH, GUDID_ONLY, or MDALL_ONLY based on merge outcome.

4. CJRR manufacturer filter and GUDID API enrichment.

   The merged dataset was filtered to manufacturers existing in the CJRR IPL, focusing the library on devices relevant to the Canadian registry context. Per-device free-text descriptions and size annotations were then retrieved from the GUDID REST API for each unique device identifier, and cached locally to minimize redundant API calls.

5. eIFU download (optional)

   eIFU PDFs were downloaded from manufacturer portals using Selenium-based browser automation. eIFU retrieval was implemented as an optional stage and can be bypassed for quicker pipeline runs.

6. eIFU material extraction

   Material composition data was extracted from downloaded eIFU PDFs using manufacturer-specific parsers, which handle the variability in formatting of material specification tables across manufacturers. Extracted values overwrite regex derived values from free-text fields, as eIFU text is considered a higher-fidelity source.

7. Supplemental CSV merge

Records from the New Zealand medical devices CSV were merged into the dataset to improve coverage for catalogue numbers absent or incomplete in GUDID and MDALL.

8. Component type classification

   Each record was assigned a component type using a rule-based classifier applied to the GMDN term, supplemented by the GUDID device name and MDALL brand name where the GMDN term was ambiguous or absent.

9. Field extraction

   Implant characteristic fields (fixation, stability, bearing type, materials, surface treatment, size, and side) were populated from free-text device descriptions, MDALL device names, and eIFU text using regex pattern matching. A catalogue-number-based size fallback was additionally applied for major manufacturers (Zimmer Persona and NexGen, Stryker, DePuy ATTUNE/Sigma, Smith & Nephew) where size, side, thickness, and stability could be decoded directly from the catalogue number format without reference to free-text descriptions (implant_library/catalogue_num_sizer_rules.md).

10. Field applicability matrix

    The applicability matrix (Table B.3) was applied to each record, marking fields as present, missing, or not_applicable based on component type. Records with any applicable field remaining missing were flagged for manual review.

11. Export and review

The final library was exported as a timestamped CSV. A companion needs_review file was generated, grouping flagged records by manufacturer, brand name, and component type, with pre-filled consensus values where all catalogue numbers in a group already agreed on a field value, and blank entries where values were absent or conflicting. Completed review files can be applied back to the library using a validation script that matches on manufacturer/brand/component group keys and, by default, fills only blank fields without overwriting existing values.

Following initial library generation, a standalone enrichment step was applied to add AP depth, ML width, insert thickness, diameter, and material data from two supplemental manufacturer-specific reference files covering Zimmer NexGen/Persona and Stryker, DePuy, Smith & Nephew, and Zimmer/Biomet systems. This step never overwrites existing non-blank values and fills lateral AP depth equal to medial AP depth for symmetric components while treating them independently for asymmetric designs.

The complete pipeline is publicly available on GitHub (https://github.com/nloughl/Implant-Library), enabling other researchers and registry custodians to reproduce the library, incorporate new implant systems, or adapt the pipeline to other national registries with different manufacturer mixes.

Appendix C

Fixation: Supplementary Material

This appendix contains supplementary material for Chapter 3.

C.1 Record Exclusion

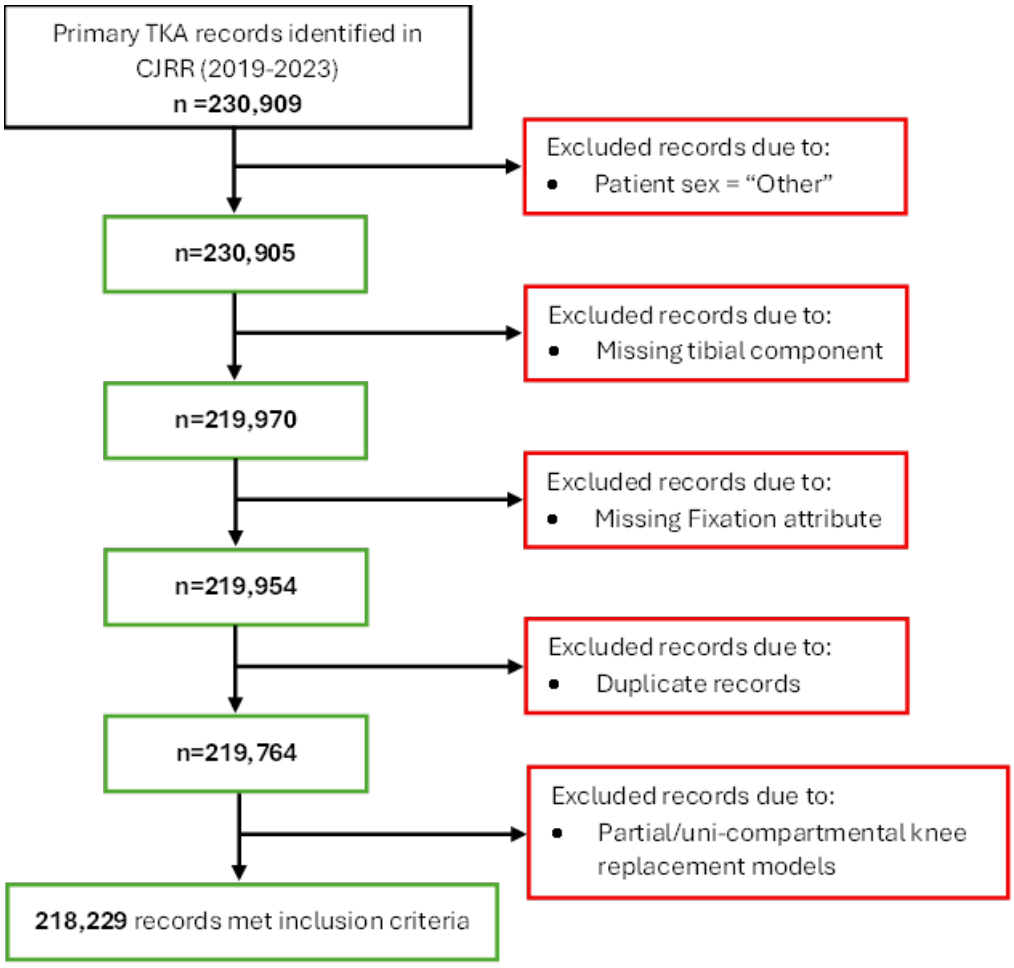


Figure C.1: Data filtering diagram accounting for the final sample size after applying the exclusion criterion.

C.2 Additional Tables

Table C.1: Sensitivity analysis: conventional reference-coded multivariable logistic regression for cementless fixation procedures (n = 218,229) with Ontario as the reference province. OR = odds ratio, CI = confidence interval. Manitoba, Saskatchewan, and the Northwest Territories were excluded from the multivariable logistic regression model due to sparse or absent observed cementless cases, preventing stable parameter estimation. Descriptive fixation rates for these provinces are reported in Table 2. Model fit: McFadden's pseudo-R^2 = 0.056, AUROC = 0.671

Predictor	**OR**	**95% CI**	**P-value**
Fiscal year (per year)	1.30	1.29-1.31	<0.001
Sex: Male vs. Female	1.59	1.55-1.63	<0.001
Age <50 (reference)	-	-	-
Age 50-60	0.80	0.73-0.86	<0.001
Age 60-70	0.60	0.55-0.65	<0.001
Age 70-80	0.40	0.37-0.43	<0.001
Age 80+	0.23	0.21-0.25	<0.001
Alberta vs. Ontario	1.61	1.55-1.67	<0.001
British Columbia vs. Ontario	1.90	1.84-1.95	<0.001
Newfoundland & Labrador vs. Ontario	0.36	0.32-0.41	<0.001
Nova Scotia vs. Ontario	1.45	1.37-1.53	<0.001

Table C.2: Pairwise comparison results of cementless fixation proportion by patient age group and sex. *P*-value adjustment method: Bonferroni. F = Female, M = Male.

Sex and age group (years)	F <50	M <50	F 50-60	M 50-60	F 60-70	M 60-70	F 70-80	M 70-80	F 80+	M 80+
M <50	0.00077									
F 50-60	0.053	<0.001								
M 50-60	0.049	0.58	<0.001							
F 60-70	<0.001	<0.001	<0.001	<0.001						
M 60-70	1.00	<0.001	<0.001	<0.001	<0.001					
F 70-80	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001				
M 70-80	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
F 80+	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		
M 80+	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	1.00	<0.001	<0.001	

Appendix D

Patellar Resurfacing: Supplementary Material

This appendix contains supplementary material for Chapter 4.

D.1 Data Filtering

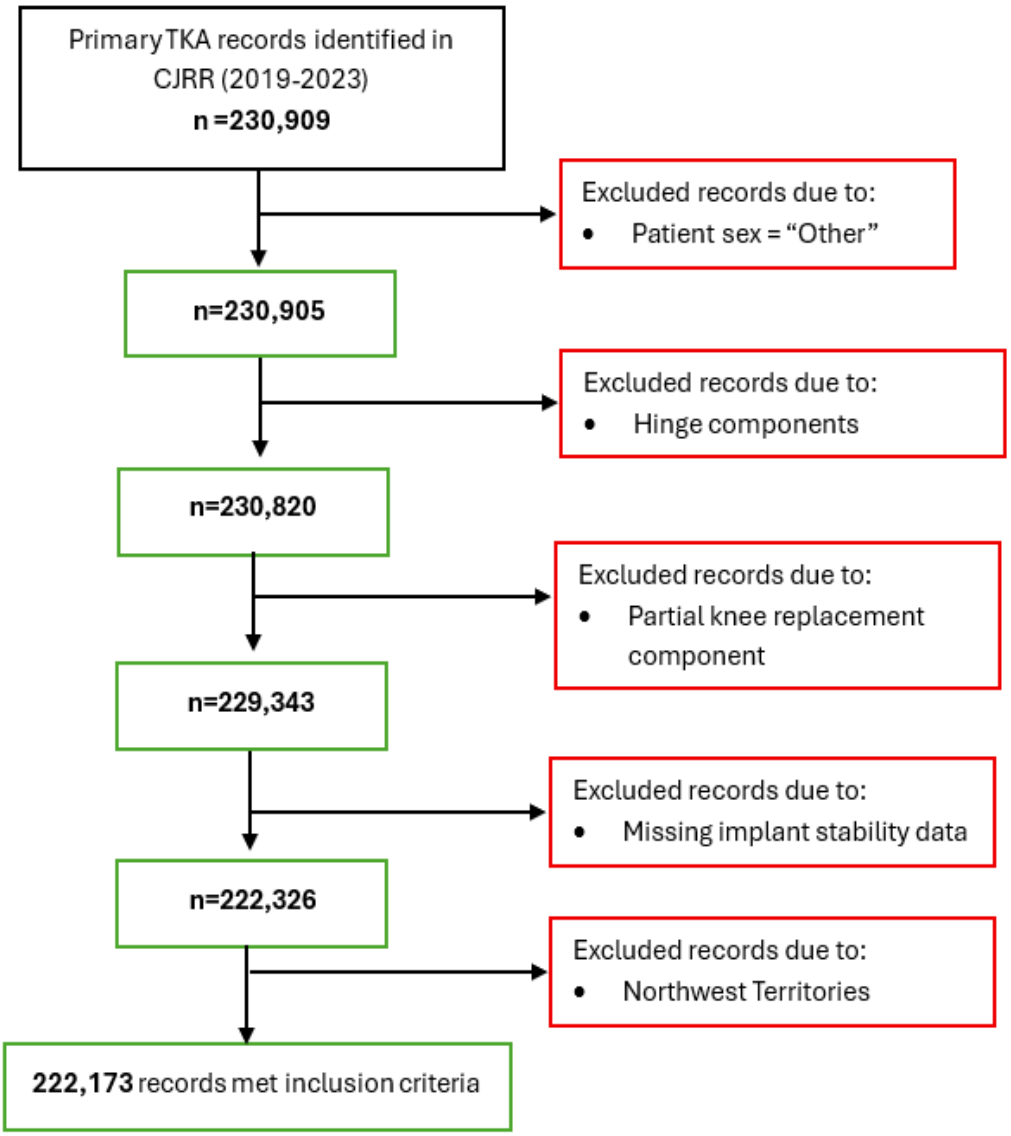


Figure D.1: Data filtering via exclusion criteria outlined in Methods.

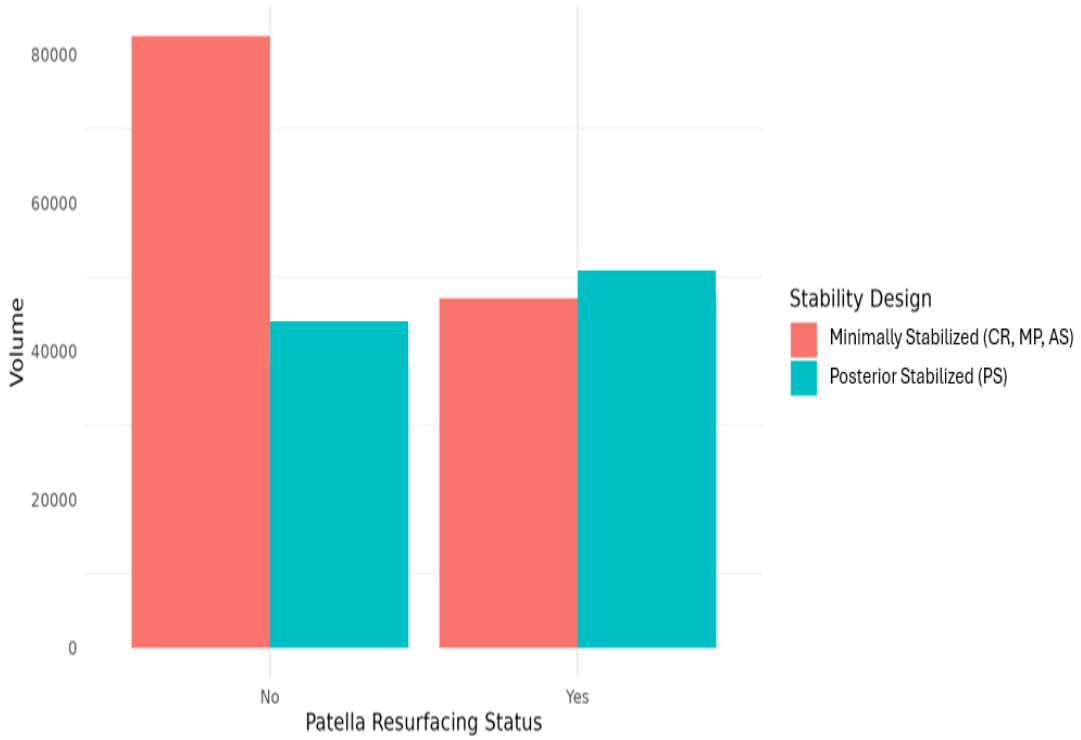


Figure D.2: Alternative patellar resurfacing and stability design cumulative utilization over the study period (2019-2023), if standard CJRR stability design groupings were used. PS = posterior stabilized; AS = anterior stabilized; CR = cruciate retaining; MP = medial pivot.

D.2 Monoblock Sensitivity Analysis

Two parallel versions of the full descriptive and inferential analysis were run on the CJRR data cohort: (1) a primary analysis that retained monoblock tibial components ("with monoblock"), and (2) a sensitivity analysis that excluded all monoblock tibial components ("without monoblock").

D.2.1 Multivariable logistic regression: predictors of patellar resurfacing

Cohort-level characteristics were nearly identical between the two versions (Table D.1). Stability-type subgroup sizes and characteristics (AS, CR, MP, PS) and yearly/provincial breakdowns were similarly closely matched, with the expected small reduction in CR and AS counts once monoblock components were removed.

Table D.1: Cohort characteristics with and without monoblock components.

Characteristic	**With monoblock**	**Without monoblock**
N	222,173	223,174*
Mean age (SD)	68.52 (8.66)	68.50 (8.66)
% Female	58.62%	58.50%
% Patella resurfacing	43.85%	43.64%
AS (n)	32,234	31,916
CR (n)	45,884	47,250
MP (n)	48,804	48,804
PS (n)	95,251	95,204

All Pearson's chi-squared and Cochran–Armitage trend tests had the same direction of effect, the same statistical significance, and near-identical effect sizes across versions:

Table D.2: Trend statistics with and without monoblock components.

Test	**With monoblock**	**Without monoblock**
Patella use, temporal trend (r)	0.085, $p < 0.001$	0.086, $p < 0.001$
PS use, temporal trend (r)	0.155, $p < 0.001$	0.156, $p < 0.001$
MP use, temporal trend (r)	0.202, $p < 0.001$	0.200, $p < 0.001$
Patella use × province (Cramer's V)	0.128, $p < 0.001$	0.125, $p < 0.001$
Stability × province (Cramer's V)	0.223, $p < 0.001$	0.222, $p < 0.001$
Patella use × age group (Cramer's V)	0.009, $p < 0.001$	0.011, $p < 0.001$
Patella use × sex (Cramer's V)	0.056, $p < 0.001$	0.057, $p < 0.001$
Patella-stability combo (Cramer's V)	0.195, $p < 0.001$	0.196, $p < 0.001$

The BC-vs-ON and ON-vs-AB pairwise provincial comparisons were the only ones that were non-significant after Bonferroni correction in either version, and this pattern was identical across both (ON-vs-AB non-significant in both; all other pairwise contrasts significant in both).

D.2.2 Multinomial regression: predictors of stability type (CR reference)

Coefficients, odds ratios, and significance patterns for AS, MP, and PS (vs. CR) were similar across the two versions for all predictors (age, gender, province, fiscal year, and the province × year interaction terms):

Table D.3: Regression metrics with and without monoblock components.

Metric	With monoblock	Without monoblock
Residual deviance (main-effects model)	509,752	512,972
AIC (main-effects model)	509,806	513,026
McFadden pseudo-R^2	0.059	0.058
Multiclass AUROC	0.632	0.632
AIC (with province × year interaction)	508,137	511,348
Multiclass AUROC (interaction model)	0.635	0.635

D.3 Multivariable Logistic Regression Sensitivity Analysis

Table D.4: Sensitivity analysis: conventional reference-encoded multivariable logistic regression for predictors of patellar resurfacing. Province odds ratios (OR) are relative to Ontario; Saskatchewan excluded from the model due to sparse anterior-stabilized counts causing separation. Model fit: McFadden's pseudo-R^2 = 0.019, AUROC = 0.588.

Predictor	OR	95% CI	
		Lower	Upper
Age at surgery (per year)	1.003	1.002	1.004
Male sex (ref: female)	0.802	0.788	0.816
Alberta (ref: Ontario)	0.978	0.901	0.945

Table D.4: Sensitivity analysis: conventional reference-encoded multivariable logistic regression for predictors of patellar resurfacing. Province odds ratios (OR) are relative to Ontario; Saskatchewan excluded from the model due to sparse anterior-stabilized counts causing separation. Model fit: McFadden's pseudo-R^2 = 0.019, AUROC = 0.588.

Predictor	OR	95% CI	
		Lower	Upper
British Columbia	1.169	1.085	1.122
Manitoba	2.434	2.215	2.382
Newfoundland & Labrador	0.330	0.290	0.334
Nova Scotia	1.055	0.957	1.037
Fiscal year (per year, centered)	0.892	0.887	0.897

Table D.5: Sensitivity analysis: conventional reference-encoded multinomial logistic regression for predictors of stability design relative to the cruciate-retaining (CR) reference category. Province odds ratios (OR) expressed relative to Ontario (reference); Saskatchewan excluded due to sparse anterior-stabilized counts. Model fit: McFadden's pseudo-R^2 = 0.059, multiclass AUROC = 0.632.

Predictor	Anterior Stabilized			Medial Pivot			Posterior Stabilized		
	OR	95% CI		OR	95% CI		OR	95% CI	
		Lower	Upper		Lower	Upper		Lower	Upper
Age at surgery (per year)	0.986	0.984	0.988	0.990	0.988	0.992	0.997	0.996	0.998
Male sex (ref: female)	0.948	0.92	0.976	1.030	1.001	1.059	1.026	1.002	1.05
Alberta (ref: Ontario)	1.025	0.972	1.081	1.039	0.988	1.092	2.181	2.099	2.268
British Columbia	2.090	2.015	2.167	2.415	2.333	2.5	1.181	1.143	1.219

Table D.5: Sensitivity analysis: conventional reference-encoded multinomial logistic regression for predictors of stability design relative to the cruciate-retaining (CR) reference category. Province odds ratios (OR) expressed relative to Ontario (reference); Saskatchewan excluded due to sparse anterior-stabilized counts. Model fit: McFadden's pseudo-R^2 = 0.059, multiclass AUROC = 0.632.

	Anterior Stabilized			**Medial Pivot**			**Posterior Stabilized**		
Predictor	**OR**	**95% CI**		**OR**	**95% CI**		**OR**	**95% CI**	
		Lower	**Upper**		**Lower**	**Upper**		**Lower**	**Upper**
Manitoba	0.159	0.131	0.194	0.875	0.795	0.963	5.878	5.494	6.289
Newfoundland & Labrador	0.371	0.338	0.408	0.205	0.184	0.228	0.438	0.41	0.467
Nova Scotia	0.866	0.813	0.924	0.037	0.03	0.046	0.975	0.928	1.024
Fiscal year (per year, centered)	1.212	1.200	1.224	1.447	1.433	1.462	0.962	0.954	0.969

Abbreviations: AS = anterior-stabilized; MP = medial-pivot; PS = posterior-stabilized; CI = confidence interval.

Appendix E

Manufacturer Trends: Supplementary Material

This appendix contains supplementary material for Chapter 5.

E.1 Record Exclusion

Hybrid constructs were captured as a distinct fixation category. However, such hybrid constructs accounted for a small share of the cohort nationally (cementless femoral and cemented tibial: n = 4,334, 2.0%; cemented femoral + cementless tibial: n = 1,491, 0.7%), and were thus not included in the fixation-disaggregated analyses due to model-level sample sizes below the 400-record threshold.

A small number of CR femoral systems (n = 87, <0.1% of CR femoral records) were recorded with posterior-stabilized (PS) tibial inserts; however, PS inserts require a femoral cam/post mechanism not present in CR femoral designs, thus this combination is not a valid clinical construct and likely reflects catalogue number mapping or data entry errors rather than a true mixed-stability implant. These records were retained in the overall dataset but interpreted with caution in insert-stability-specific analyses.

Similarly, mixed manufacturer systems wherein a tibial baseplate from one manufacturer and a femoral component from another were reported existed in a small number in the dataset. These constructs are generally invalid and were filtered out of the analyses based on the minimum construct sample-size threshold defined above.

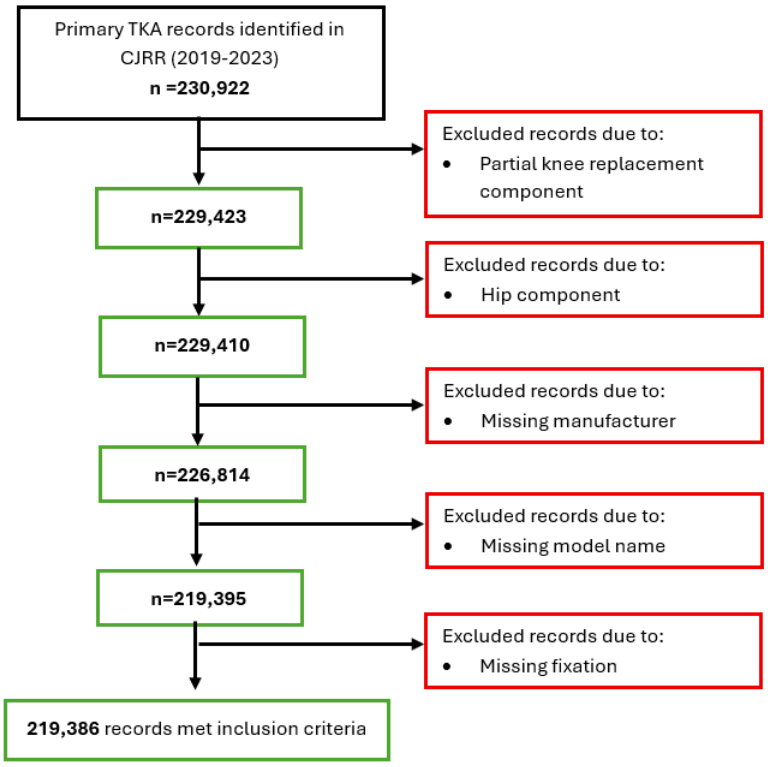


Figure E.1: Data inclusion and exclusion diagram.

E.2 Model-Family Analyses

For model-family level analyses, tibial baseplate and femoral component models were identified via catalogue number and were reported as the manufacturer-specified brand name of the device (e.g. Persona, Attune, etc.). Model families with fewer than 1,000 total pro-

cedures were grouped together in the "Other" category to protect potentially identifiable information.

Most TKA systems used the same model family for both the femoral and tibial components (e.g., Persona + Persona). However, some manufacturers use different family names for their compatible femoral and tibial components; for example, Smith & Nephew's Legion femoral components are compatible with, and commonly paired with, Genesis II tibial components (Legion + Genesis). Such systems with mixed (but manufacturer-approved) model families were relatively uncommon (7.5%).

Mirroring the manufacturer trends, analysis of the femoral-tibial TKA model combinations showed 2 primary systems (femoral + tibial): Persona + Persona (Zimmer, 38.2%), and Triathlon + Triathlon (Stryker, 35.1%) (Fig. E.2). The five most common model combinations nationally were manufactured by four companies: Persona and NexGen (Zimmer), Triathlon (Stryker), Legion + Genesis (Smith & Nephew), and Evolution (MicroPort). Notably, Zimmer was the only manufacturer represented by two distinct systems among these five combinations (Persona + Persona and NexGen + NexGen), consistent with Zimmer's overall manufacturer-level market dominance. A Pearson's chi-squared goodness-of-fit test confirmed a significant difference from a uniform model distribution (χ^2 = 2,627,427, df = 45, $p < 0.001$). A Cochran-Armitage trend test of the model systems across fiscal years showed significant increases in market share for the Persona + Persona (χ^2 = 3,345.0, $p < 0.001$) system, no significant change for Triathlon + Triathlon (χ^2 = 0.5, $p = 0.46$), and significant decreases in market share for the NexGen + NexGen (χ^2 = 3,246.8, $p < 0.001$), Legion + Genesis (χ^2 = 11.9, $p < 0.001$), and Genesis + Genesis (χ^2 = 13.8, $p < 0.001$) systems.

Significant provincial variation in TKA implant models was also found (χ^2 = 129680, $p < 0.001$, Fig. E.2). The market of most provinces is dominated by a 1 or 2 models. However, the Saskatchewan and Northwest Territories markets are comprised of nearly a single model system (Persona + Persona in Alberta, and Genesis + Genesis in the Northwest Territories). Unlike the other provinces, the Northwest Territories used Genesis models, which are sparsely used throughout the rest of the country. Similarly, Manitoba had a greater proportion of Legion + Genesis models, a combination uncommon in other

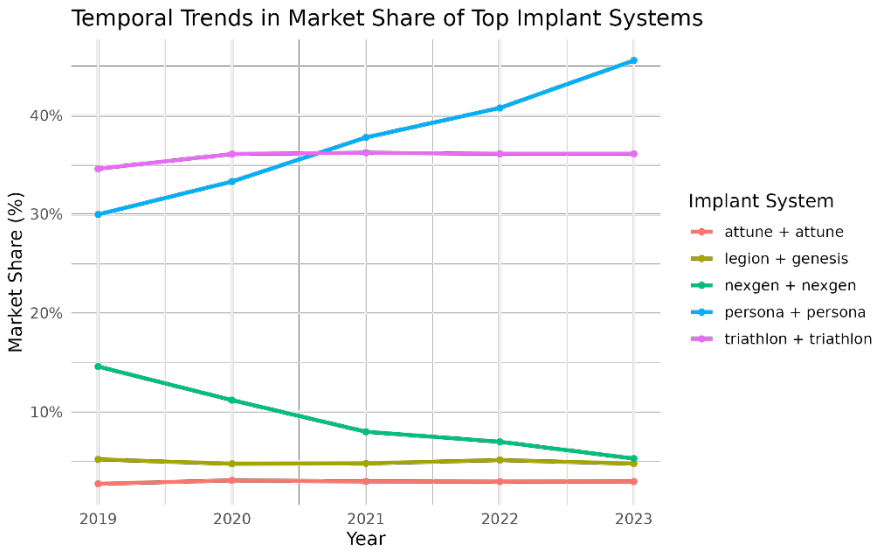


Figure E.2: Femoral + Tibial component model market share across fiscal years (2019-2023).

provinces (Fig. E.3).

E.3 Component Disaggregated Trends

Disaggregation by component type (femoral and tibial) shows a more granular breakdown of the implant system trends. Among the femoral components (Fig. E.4), the Zimmer Persona Cemented CR model showed a substantial increase in utilization over the study period, accounting for approximately 11% of the market share in 2019 to 34% in 2023. The Stryker Triathlon CR with PA (peri-apatite) coating model market share also increased over time from approximately 5% to 14%. Other models, such as the Zimmer Persona Cemented PS, Stryker Triathlon CR, and Stryker Triathlon, decreased in utilization from 2019 to 2023. The remaining models maintained relatively stable market shares below approximately 5% throughout the study period.

Among tibial components (Fig. E.5), the Zimmer Persona (cemented) model was most frequently used across all years and increased from approximately 30% market share to

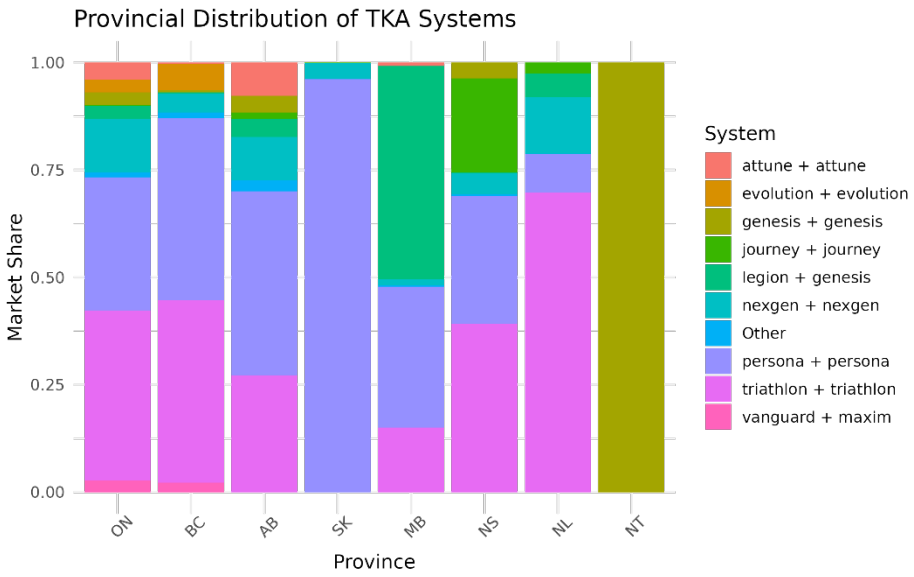


Figure E.3: Provincial femoral + tibial model distribution.

43% from 2019 to 2023. The Stryker Triathlon Tritanium (cementless) also increased in use over the study period, but to a lesser extent, accounting for approximately 12% of the market share in 2019 to 18% in 2023. In contrast, models such as the Stryker Triathlon Cemented and Zimmer Nexgen PS and CR Precoat Stemmed tibial components decreased market shares over the study period. The remaining models had relatively stable market shares below approximately 5% from 2019 to 2023.

This disaggregation by component type showed nuances in model-level adoption patterns (Figs. E.4 and E.5). The contrasting trajectories of Triathlon Tritanium (cementless, increasing) and Triathlon Cemented tibial components (decreasing) suggest a shift toward cementless tibial fixation. Similarly, the Stryker Triathlon femoral components showed the same pattern, with the cementless Triathlon CR with PA (peri-apatite) coating femoral component increasing in use and cemented Triathlon femoral models decreasing (Fig. E.4). Again, this shows that despite stable model-family level trends (Fig. E.2), component-level shifts occurred.

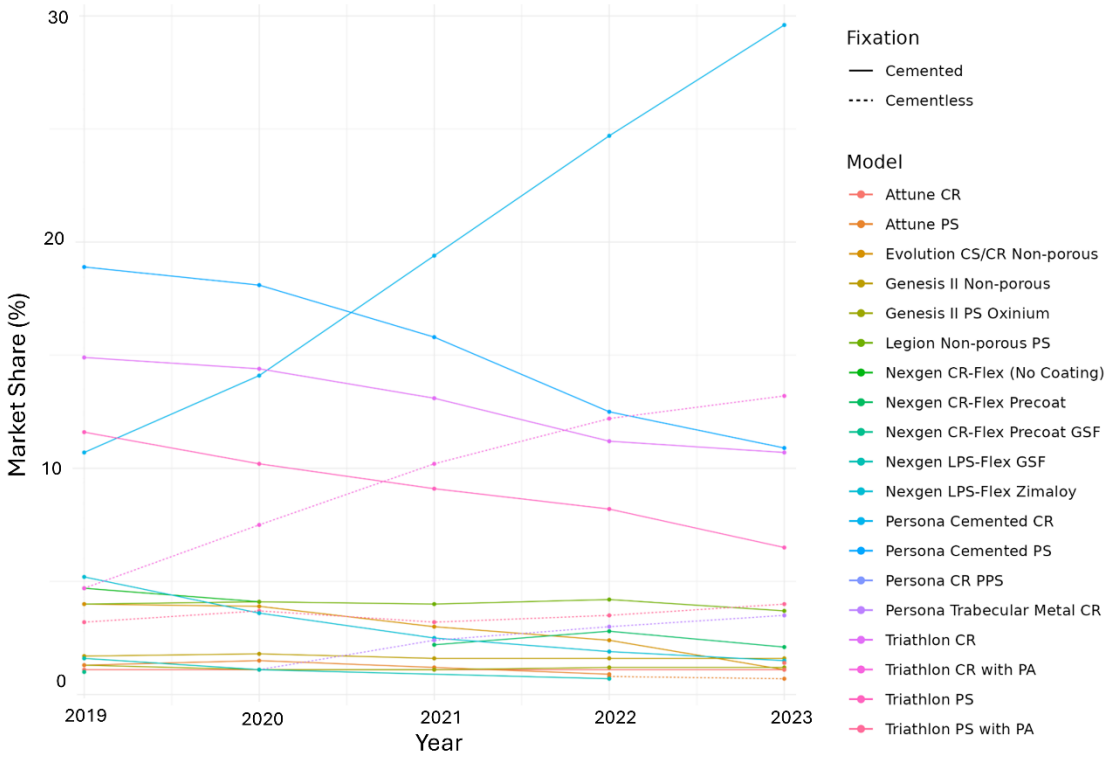


Figure E.4: Femoral component model distribution across fiscal years. CR = Cruciate Retaining, PS = Posterior Stabilized, PA= Peri-Apatite; Persona and NexGen = Zimmer, Triathlon = Stryker, Attune = DePuy, Evolution = MicroPort. Cemented and cementless variants are distinguished by line type.

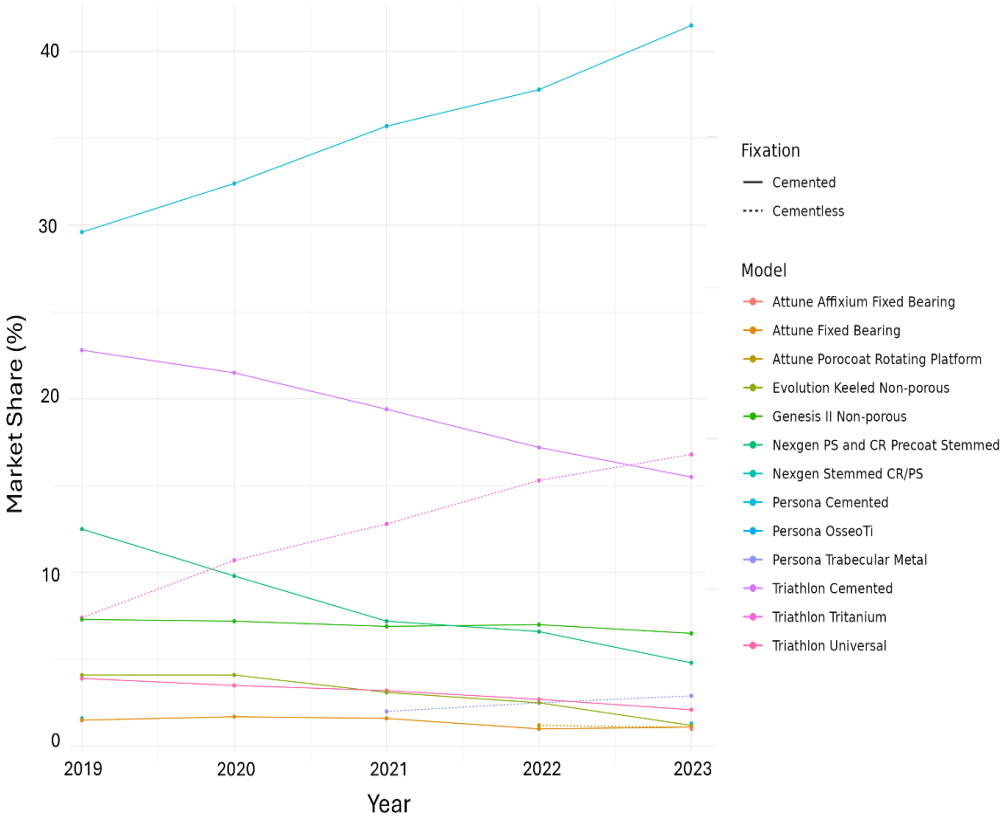


Figure E.5: Tibial component model distribution across fiscal years. CR = Cruciate Retaining, PS = Posterior Stabilized; Persona and NexGen = Zimmer, Triathlon = Stryker, Attune = DePuy, Evolution = MicroPort. Cemented and cementless variants are distinguished by line type.

E.4 Ontario Sensitivity Analysis

Sensitivity analyses excluding Ontario (n = 107,536), which accounted for approximately half of the national procedure volume (n = 111,850 of 219,386; Table 5.3), showed broadly consistent findings with the primary national analysis (Fig. E.6). Zimmer's increasing market share (Cochran-Armitage $\chi^2 = 573.5$, $p < 0.001$; 48.0% in 2019 to 57.8% in 2023) and MicroPort's decline ($\chi^2 = 1{,}266.7$, $p < 0.001$; 6.7% to 0.7%) remained statistically significant (Fig. E.7). The interprovincial variation in manufacturer distribution was also consistent ($\chi^2 = 55{,}648$, df = 54, $p < 0.001$, Cramer's V = 0.29). Unlike the national analysis, Stryker showed a statistically significant decline in market share outside Ontario ($\chi^2 = 131.6$, $p < 0.001$; 31.4% in 2019 to 27.8% in 2023) compared to nationally (35.2% to 34.5%), suggesting that Ontario's comparatively stable Stryker utilization moderates the manufacturer's apparent national trend. DePuy showed a significant increase outside Ontario (linear regression $\beta = +0.46\%$/year, $p = 0.02$; Cochran-Armitage 1.9% in 2019 to 3.8% in 2023, $p < 0.001$), contrasting with its non-significant national trend (β = -0.05%/year, $p = 0.72$), indicating that Ontario disproportionately influences DePuy's apparent national trend. Also of note, several smaller-volume manufacturers, including Ceraver, Corin, and Link, were represented only in Ontario and were therefore absent from the analysis when Ontario was excluded. However, utilization of implants from these manufacturers was sufficiently low that their models were not included in the model-level or manufacturer-level analyses. National HHI excluding Ontario was similar to the full-dataset value in 2019 (3,485 vs. 3,605) but diverged further by 2023 (4,230 vs. 3,962), indicating that market concentration outside Ontario increased more steeply over the study period. Overall, these findings suggest that while Ontario's volume shapes the precise magnitude of national estimates (particularly for Stryker and DePuy), the overall conclusions of the primary analysis are largely robust to its exclusion.

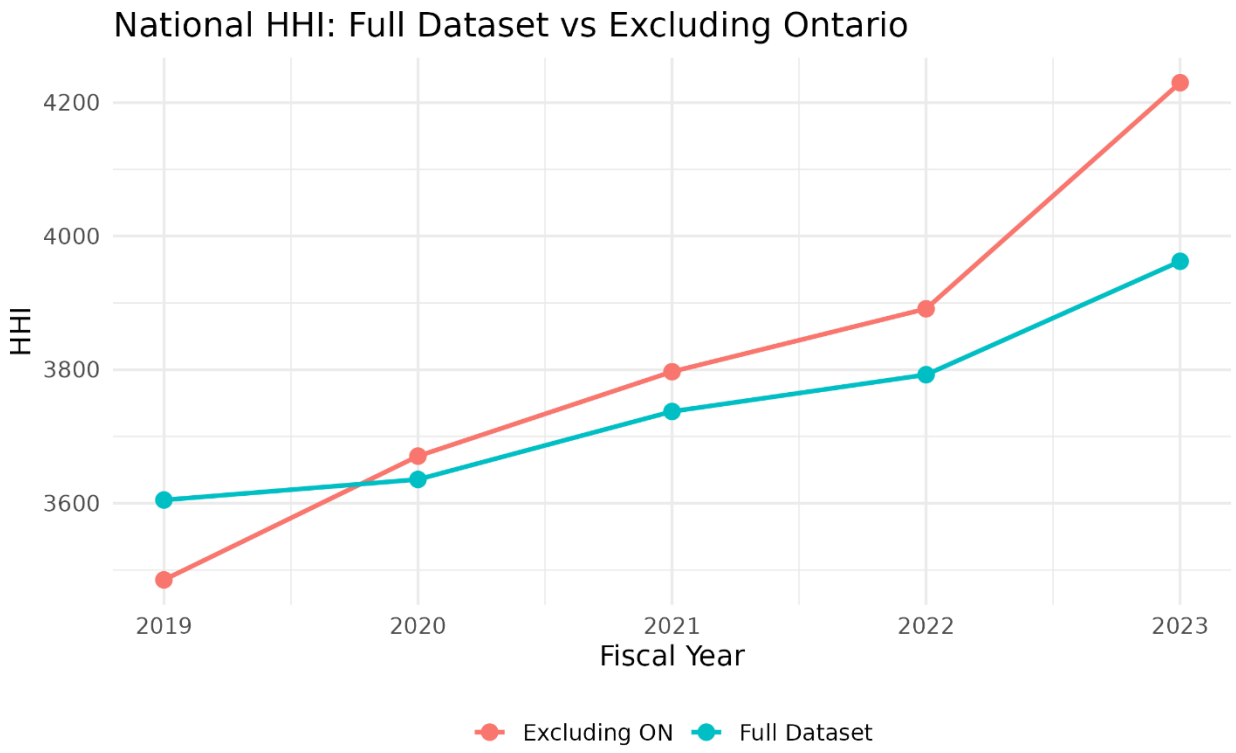


Figure E.6: National market concentration (HHI) including (blue) and excluding (red) Ontario.

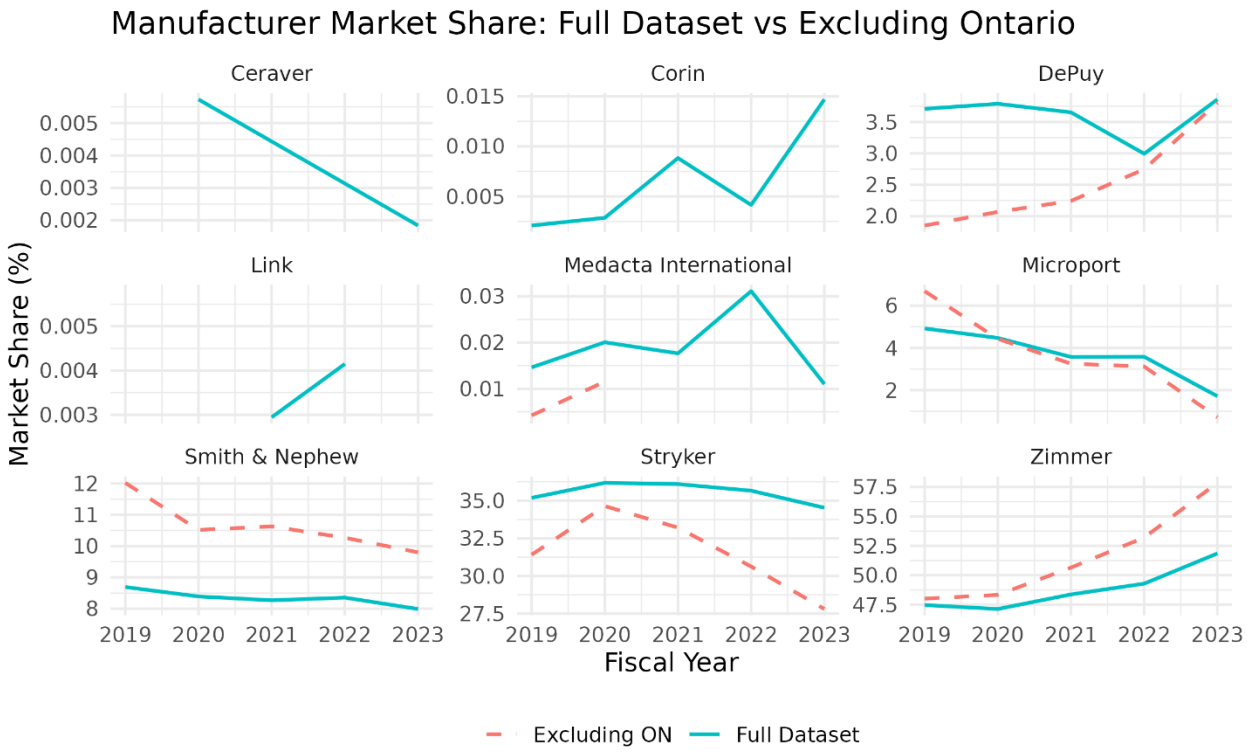


Figure E.7: Manufacturer market share over fiscal years including (blue) and excluding (red) Ontario.

Appendix F

Clustering: Supplementary Material

This appendix contains supplementary material for Chapter 6. Numbered citations refer to the reference list at the end of that chapter.

This appendix summarizes supplementary exploratory data analysis (EDA), method-comparison test runs, and sensitivity-analysis outputs referenced in the Results and Discussion.

F.1 Data inclusion and exclusion criteria

Outliers were identified in numerical variables using the QIR x 1.5 rule [18]. Table F.1 reports the variables assessed, the IQR, and the number of outliers for each variable.

Table F.1: Outlier identification results for numeric clustering variables.

Variable	**IQR**	**Outliers (n)**
Femoral AP/ML Ratio	[0.6,1.14]	12
Femoral AP/ML Ratio	[0.58,0.78]	0
Insert Thickness	[7,15]	8936

To address high cardinality of variables and sparse counts, rare levels were collapsed into an "other" category if they did not meet the minimum count (n = 30). If the collapsed levels still did not meet the minimum threshold, those rows were removed. Table F.2 describes the variable collapse.

Table F.2: Collapsing rare levels results.

Variable	**Levels**	**Met Minimum Count**
Femoral Model	GMRS, Journey, LCS fs, LCS ps, S ROM	Yes
Femoral Metal Material	CoCr + Tantalum	No
Insert Mobility	Rotating Hinge	No
Insert Polyethylene Material	UHMWPE + AOX	No
Stability	Fully Stabilized	No

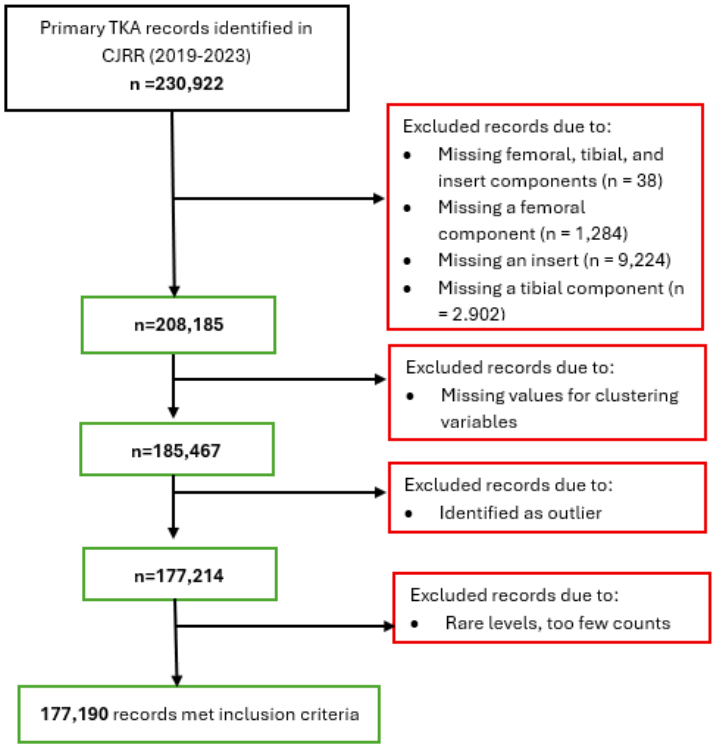


Figure F.1: Data filtering according to the exclusion criteria.

F.2 Pre-Clustering Exploratory Data Analysis

Missingness across the 208,185-procedure cohort (before applying exclusion criteria) was concentrated in a small number of fields (Fig. F.2). Exploratory FAMD on the full 29-variable candidate set (prior to redundancy-based reduction) found that the first five dimensions explained only 13.2% of total variance (Fig. F.4), motivating the subsequent variable-reduction step described in Methods.

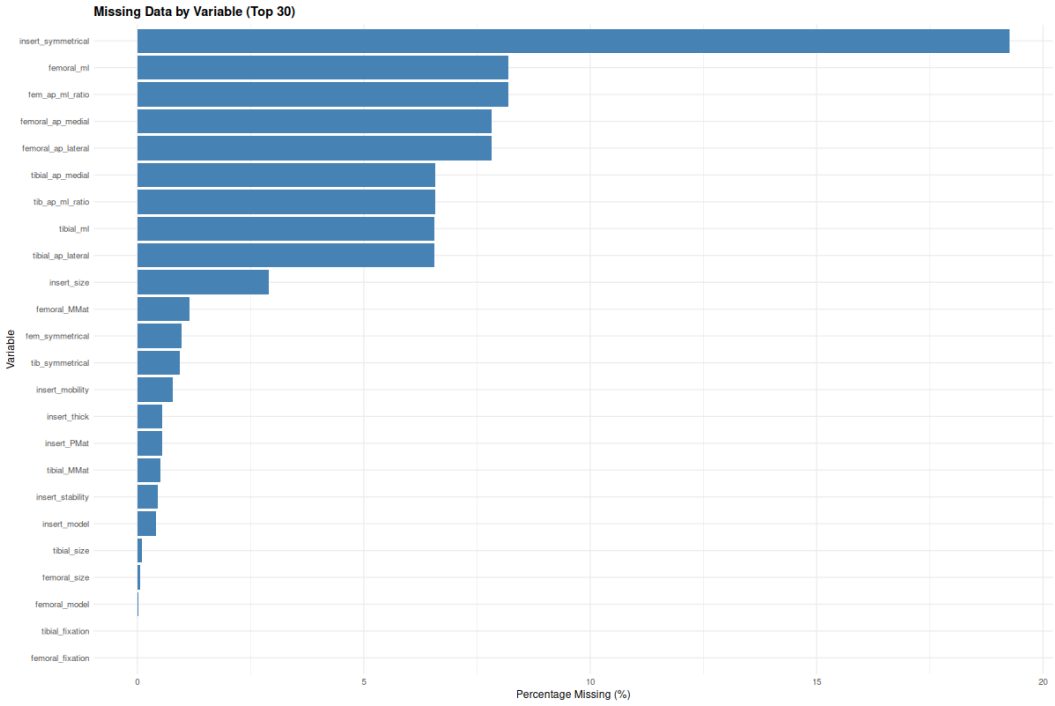


Figure F.2: Missing data pattern across candidate clustering variables, full cohort (n = 208,185).

F.2.1 Data Preparation

Redundancy screening identified femoral and tibial fixation as highly associated (Cramér's V = 0.91), femoral, tibial, and insert manufacturer identity as strongly associated with one

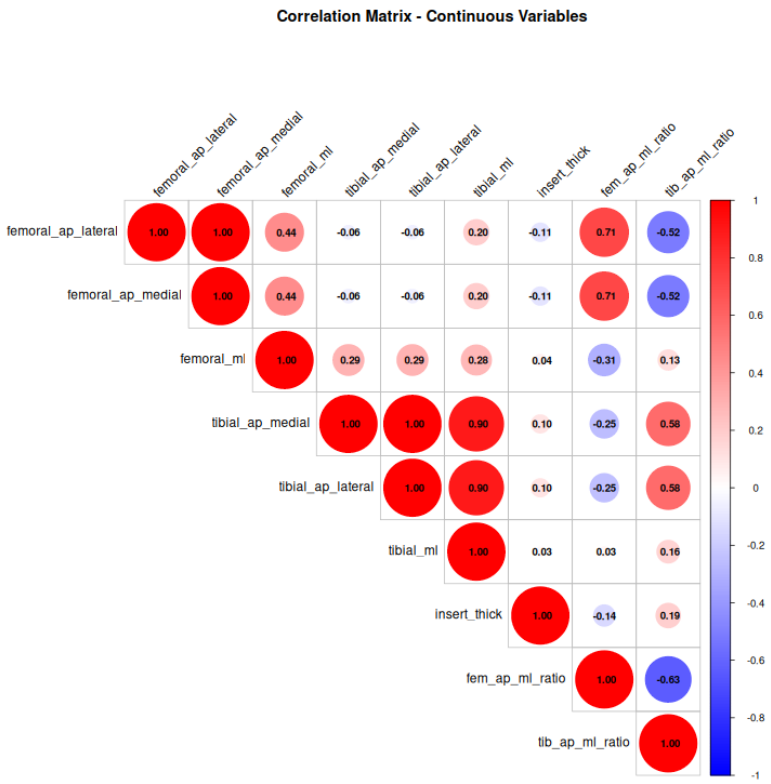


Figure F.3: Correlation matrix, candidate continuous clustering variables..

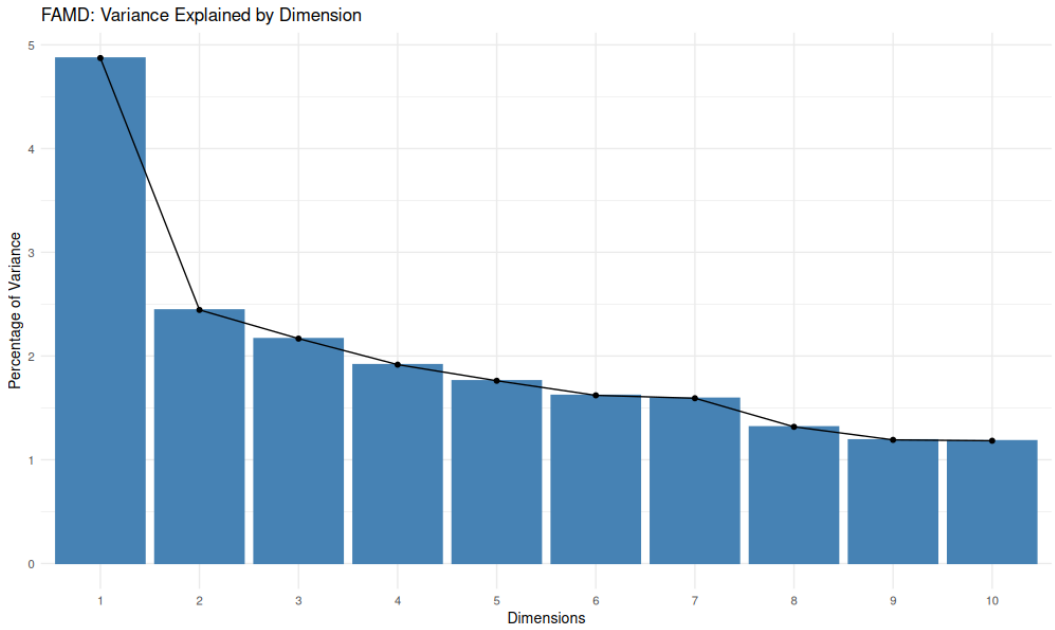


Figure F.4: FAMD scree plot, full 29-variable candidate set (pre-reduction).

another (Cramér's V = 0.71-0.71) and with model name (Cramér's V = 0.63-0.78), and femoral AP-lateral and AP-medial measurements as perfectly correlated (r = 1.00). One variable from each redundant pair or group was retained (tibial fixation; femoral model; a single femoral AP measurement). Tibial fixation was selected over femoral fixation as the tibial component is more often associated with adverse outcomes in cementless TKA [42] and thus, retaining the tibial fixation variable may provide greater insight into which patient or procedural characteristics are associated with receipt of these components. Femoral and tibial AP and ML dimensions were also highly correlated ($r > 0.85$, Fig. F.3), and correlations among the AP measurements and their corresponding component AP/ML ratios were also moderately correlated (femoral AP/ML vs femoral AP: r = 0.71; and tibial AP/ML vs tibial AP: r = 0.58). Considering the correlation among the dimensional variables, only the AP/ML ratios were retained, as they captured both dimensions while minimizing the influence of implant size. This aimed to account for potential confounding by sex, as the literature has reported established sex differences in implant size use by sex (mainly attributable to anatomical differences) [43 –46] and the size-dependency of

the raw AP and ML dimensions. Inclusion the ratio rather than the raw measurements in clustering allowed the analysis to remain focused on implant configuration rather than patient demographics, only examining patient demographics in post-hoc analyses of the clustering solution.

To evaluate whether the femoral and tibial AP/ML ratio variables adopted for Question B could meaningfully substitute for femoral model identity, one-way ANOVA was used to test whether femoral model explained variation in each ratio. Femoral model explained a substantial share of variance in both the femoral ($\eta^2 = 0.72$, 95% CI: 0.72, 1.00) and tibial ($\eta^2 = 0.78$, 95% CI: 0.77, 1.00) AP/ML ratios (both $p < 0.001$) indicating that implant shape, as captured by the AP/ML ratio, closely tracked model identity even though model name is not used directly as a clustering input in Question B. Levene's test indicated significant heterogeneity of variance across models for both ratios ($p < 0.001$), thus, results were confirmed using Welch's ANOVA (does not assume equal variances). The analysis was further restricted to the most frequently used implant models to reduce the effect being driven by small, rare-model categories. The findings of both analyses were consistent with the original effect sizes. Femoral and tibial AP/ML ratios were moderately correlated with one another ($r = -0.634$), but below the redundancy threshold, suggesting they capture some independent dimensions of implant shape, and were therefore retained as separate clustering variables in Question B. This preliminary analysis also confirmed that removing manufacturer/model from the Question B variable set may not necessarily discard the design-relevant shape information that the implant model name partly encodes. Thus, the AP/ML ratios were a reasonably defensible, brand-agnostic substitute (full test outputs in Section F.3).

F.3 AP & ML Variable Investigation

An additional investigation examined the effect of excluding femoral/tibial AP and ML measurements from the Question A variable set. Specifically, this analysis assessed whether using different variable sets for Question A and Question B for both missing-data removal

and subsequent clustering would substantially affect the resulting clusters. On an initial, unmatched comparison, excluding AP and ML variables increased the optimal k from 5 to 7 and produced a cluster that was approximately 70% male, versus approximately 60% female in all clusters of the AP and ML-included solution. Further review found this apparent sex effect was an artifact of differential missingness between the two samples (the additional cluster was composed entirely of procedures with missing AP and ML fields that had been dropped from the Question B cohort). On a matched, complete-case sample, excluding AP and ML variables from the Question A dataset produced six clusters with no meaningful sex difference; the additional cluster (relative to the AP and ML-included solution) was instead distinguished by femoral implant model and submitting province.

Thus, although Questions A and B used different variable sets, both analyses were restricted to procedures with complete data across the union of both variable sets. Restricting both cohorts to the same sample allowed subsequent cross-tabulation to reflect differences in clustering structure rather than differences in sample composition.

A province-by-model cross-tabulation found Saskatchewan to be a near-single-supplier outlier, with 98% of Saskatchewan procedures using a single femoral model (Persona), while Ontario showed a diverse model mix; the province-model association was moderate overall (Cramér's V = 0.27). Considering this association and that the AP and ML measurements are model-specific, the raw AP and ML measurements were excluded from the Question A variable set, and an AP/ML ratio variable was retained for Question B.

Table F.3: One-way ANOVA: femoral/tibial AP/ML ratio by femoral model (full model set, prior to dropping rows with missing data).

Ratio	**Groups (df)**	**Residual df**	**F**	**p**	η^2	**95% CI**	**n excluded (missing)**
Femoral AP/ML	17	191,106	28,874	< 0.001	0.72	0.72-1.00	17,061
Tibial AP/ML	21	194,480	31,993	< 0.001	0.78	0.77-1.00	13,683

Table F.3 suggests that the femoral model explained 72-78% of the variance in each AP/ML ratio.

Table F.4: Between- vs. within-model variance decomposition

Ratio	Between-model variance	Within-model variance	Between/within ratio
Femoral AP/ML	0.00725	0.01971	0.37
Tibial AP/ML	0.00043	0.00014	3.07

The tibial ratio seemed to separate models more sharply relative to within-model spread than the femoral ratio.

Table F.5: Levene's test for homogeneity of variance across models (restricted to the most frequently used models, to guard against small-n groups)

Ratio	df	F	p
Femoral AP/ML	11	9,509.6	$<$0.001
Tibial AP/ML	12	6,635.4	$<$ 0.001

Significant heteroscedasticity was observed in both cases. Standard ANOVA p-values may thus be unreliable; so it was addressed using Welch's ANOVA (Table F.7).

Table F.6: Robustness checks: restricted-model ANOVA (top models only) and Welch's ANOVA (unequal variances)

Ratio	Restricted ANOVA df	Restricted F	Restricted η^2 [95% CI]	n excluded	Welch's F	Welch's p
Femoral AP/ML	11	44,602	0.72 [0.72, 1.00]	16,997	161,557	< 0.001
Tibial AP/ML	12	55,954	0.78 [0.77, 1.00]	13,666	622,545	< 0.001

Welch's ANOVA used a further-restricted group count (8 models) than the standard restricted-model check (12-13 models); effect sizes and significance were unchanged across both corrections, indicating the finding is not an artifact of rare-model categories or unequal variances.

Table F.7: Correlation between femoral and tibial AP/ML ratios

Pair	r
Femoral AP/ML ratio × Tibial AP/ML ratio	-0.634

As shown in Table F.7, there was a moderate negative correlation, though it was below the $r > 0.85$ redundancy threshold; therefore, both ratios were retained as separate Question B clustering variables. Nevertheless, the relationship was not negligible and should thus not be treated as completely independent. This aligns with clinical reasoning, as femoral and tibial components must articulate via the tibial insert; thus, their general proportions must be reasonably congruent.

F.4 Clustering Method Testing and Selection

F.4.1 Selecting the Final Clustering Method

For each clustering run (Question A, Question B, and sex-disaggregated analyses), the following process was applied: (1) all four candidate clustering methods were run on a subsample of n = 10,000 procedures of for k = 2-10; (2) the optimal number of clusters (k) was selected separately for each clustering method; (3) mean Jaccard coefficients and silhouette widths were calculated for each method at its selected k; (4) clustering methods were compared primarily on mean Jaccard coefficient, with silhouette width and clinical interpretability considered as secondary criteria to select the best-performing method; and (5) the selected clustering method was applied to the full dataset, evaluating k = 2-10, again selecting the optimal k using the same criteria. These steps are described in greater detail below.

F.4.2 Determining the Number of Clusters

For each clustering method (k-prototypes, KAMILA, FMAD with k-means), a range of clustering candidate solutions (k (number of clusters) = 2 through 10) were evaluated. For the centroid- and distance-based methods (K-Prototypes, KAMILA, FAMD with k-means), the optimal number of clusters was selected using silhouette width [26], elbow inspection of within-cluster cost as a function of k, and a minimum cluster-size (n = 30) guard applied prior to any automated elbow selection, since automated selection based on the minimum of successive differences in cost proved unreliable at this sample size and could favour degenerate solutions with very small clusters.

For LCA, model selection was instead informed by the Bayesian Information Criterion (BIC) and classification entropy metrics from the poLCA R package [27]. One limitation of BIC is that its complexity penalty grows with the logarithm of sample size; thus, its practical discriminating power weakens at large sample sizes [28]. Considering this, entropy and the clinical interpretability of clusters were also considered in the selection of the number of

latent classes. Candidate solutions were also manually reviewed for clinical interpretability rather than relying solely on the location of an information-criterion minimum.

F.4.3 Cluster Stability and Method Selection

Cluster stability was quantified by the mean Jaccard coefficient using bootstrap resampling via the clusterboot function in the fpc R package [29]. Fifty resamples (B = 50) were drawn with replacement from a single fixed base subsample (n = 10,000) of the full dataset. The same base sample was used for all four clustering methods assessed to ensure comparability. For each resample, the clustering procedure was rerun from scratch, including model fitting and random initialization where applicable. For K-Prototypes, KAMILA, and FAMD with k-means, clusters were matched to the original solution by maximum membership overlap (using fpc's clusterboot). For LCA, a custom greedy proportion-matching procedure was used to resolve label-switching before calculating Jaccard coefficients.

Comparisons of the mean Jaccard coefficients followed established stability benchmarking thresholds (mean Jaccard coefficient ≥ 0.75 = stable, and > 0.85 = highly stable) [14,30]. Solutions generated by the four algorithms (k-prototypes, FAMD with k-means, KAMILA, and LCA) were compared using Gower-distance silhouette scores for each method's optimal k solution (determined by the criteria outlined above), allowing comparison of cluster separation despite differing underlying algorithms. Gower distance was used here only as a common external metric for comparing the separation across methods, not as the optimization criterion for clustering methods that do not use Gower distance (e.g. KAMILA).

F.4.4 Method-Comparison Test Runs (n = 10,000 Samples)

Before full-dataset clustering, all four candidate methods were run on 10,000-procedure test samples for each clustering specification (Question A, Question B) to select the best-performing method. Results are summarized in Table F.8.

Table F.8: Cross-method comparison, 10,000-procedure test samples. Silhouette and Jaccard computed on Gower distance (categorical-only for LCA; mixed for other methods). LCA solutions show comparatively high silhouette but low bootstrap stability across both specifications and were not selected as the primary method on that basis.

Specification	Method	k	Mean silhouette	Mean Jaccard
Question A	K-Prototypes	5	0.328	0.408
Question A	KAMILA	7	-0.017	0.411
Question A	FAMD + k-means	8	0.404	0.588
Question A	LCA	6	0.474	0.106
Question B	K-Prototypes	4	0.350	0.411
Question B	KAMILA	3	0.041	0.872
Question B	FAMD + k-means	3	0.463	0.557
Question B	LCA	6	0.425	0.138

For the final full-dataset FAMD with k-means solutions, silhouette width was evaluated across k = 2-10 (Figures D1, D2); both specifications selected k = 6 as the silhouette-maximizing, minimum-cluster-size-compliant solution.

Latent class model selection (Table F.9) illustrates the BIC behaviour discussed in Methods and Discussion: BIC continued to decrease through k = 10 in both specifications, without a clear minimum, consistent with BIC's weakened complexity penalty at this sample size rather than genuinely unbounded latent structure.

Table F.9: LCA fit statistics by number of classes (k), 10,000-procedure test samples. BIC does not reach a clear minimum by k = 10 in either specification (Kaplan et al., 2022).

k	QA BIC	QA entropy	QB BIC	QB entropy
2	98,204	4.91	85,203	4.26

Table F.9: LCA fit statistics by number of classes (k), 10,000-procedure test samples. BIC does not reach a clear minimum by k = 10 in either specification (Kaplan et al., 2022).

k	QA BIC	QA entropy	QB BIC	QB entropy
3	94,149	4.70	82,051	4.09
4	93,478	4.67	79,058	3.94
5	88,846	4.41	78,656	3.92
6	84,385	4.17	77,571	3.84
7	88,938	4.39	76,970	3.81
8	83,150	4.09	77,107	3.81
9	82,740	4.06	77,713	3.83
10	81,789	4.00	76,872	3.78

F.5 Cluster Characterization

Table F.10: Question A cluster (k=6) characterization

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
n (%)	41,610 (23.5%)	51,321 (29.0%)	89 (0.1%)	12,802 (7.2%)	1,595 (0.9%)	69,773 (39.4%)
Implant Characteristics						
Femoral model	Triathlon (99.9%)	Triathlon (56.4%)	Other/mixed (58.4%)	Legion (73.1%)	Attune (67.2%)	Persona (100%)
Tibial fixation	Cementless (61.4%)	Cemented (99.0%)	Cemented (100%)	Cemented (99.9%)	Cemented (51.0%)	Cemented (100%)
Insert stability	AS (66.4%)	PS (56.6%)	Hinged (68.5%)	PS (89.8%)	CR (42.2%)	MP (49.7%)

Table F.10: Question A cluster (k=6) characterization

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Insert mobility	Fixed (100%)	Fixed (100%)	Rotating (79.8%)	Fixed (100%)	Rotating (100%)	Fixed (100%)
Tibial symmetry	Symmetric (100%)	Symmetric (100%)	Symmetric (88.8%)	Asymmetric (99.7%)	Symmetric (100%)	Asymmetric (100%)
Femoral metal material	CoCr (100%)	CoCr (99.4%)	CoCr (88.8%)	CoCr (89.9%)	CoCr (100%)	CoCr (100%)
Tibial metal material	Titanium (61.3%)	CoCr (66.0%)	CoCr (88.8%)	Titanium (100%)	CoCr (99.9%)	Titanium (100%)
Insert polyethylene material	XLPE+AOX (37.8%)	UHMWPE (81.0%)	UHMWPE (88.8%)	UHMWPE (93.5%)	XLPE+AOX (65.1%)	XLPE+AOX (74.5%)
Patella resurfaced	No (73.8%)	No (53.0%)	No (68.5%)	Yes (64.7%)	No (84.3%)	Yes (53.0%)
Femoral stem	No (99.7%)	No (98.3%)	No (73.0%)	No (99.7%)	No (97.9%)	No (99.2%)
Tibial stem	No (100%)	No (97.5%)	No (94.4%)	No (99.4%)	No (99.7%)	No (95.3%)
Insert thickness (mm)	10.11 ± 1.39	10.50 ± 1.45	11.43 ± 1.44	11.51 ± 1.85	9.49 ± 2.15	10.97 ± 1.25
Femoral AP/ML ratio	1.00 ± 0.09	0.98 ± 0.08	0.91 ± 0.06	0.90 ± 0.01	0.93 ± 0.02	0.79 ± 0.03

Table F.10: Question A cluster (k=6) characterization

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Tibial AP/ML ratio	0.665 ± 0.013	0.660 ± 0.021	0.674 ± 0.022	0.702 ± 0.005	0.656 ± 0.002	0.709 ± 0.005
Demographics						
Sex (% female)	57.2%	61.1%	73.0%	58.5%	52.4%	59.2%
Submitting province (top)	ON (53.6%)	ON (64.2%)	AB (36.0%)	ON (43.8%)	AB (59.6%)	ON (41.2%)
Diagnosis (% OA)	99.2%	98.7%	79.8%	98.8%	98.8%	98.7%
Age at surgery (years)	67.75 ± 8.55	69.54 ± 8.56	69.17 ± 13.32	68.42 ± 8.69	67.83 ± 8.89	68.86 ± 8.55
Fiscal year	2021.32 ± 1.45	2020.65 ± 1.47	2020.71 ± 1.44	2021.01 ± 1.50	2020.83 ± 1.40	2021.28 ± 1.47

Table F.11: Question B cluster characterization (k = 6).

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
n (%)	63,789 (36.0%)	25,219 (14.2%)	2,700 (1.5%)	1,655 (0.9%)	43,345 (24.5%)	40,482 (22.8%)
Implant Characteristics						
Tibial fixation	Cemented (98.8%)	Cementless (99.9%)	Cemented (99.6%)	Cemented (52.7%)	Cemented (99.8%)	Cemented (100%)

Table F.11: Question B cluster characterization (k = 6).

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Insert stability	PS (43.2%)	AS (50.9%)	VVC (46.1%)	CR (40.7%)	PS (87.3%)	MP (85.1%)
Insert mobility	Fixed (100%)	Fixed (100%)	Fixed (99.3%)	Rotating (99.5%)	Fixed (100%)	Fixed (100%)
Tibial symmetry	Symmetric (100%)	Symmetric (99.9%)	Symmetric (63.1%)	Symmetric (100%)	Asymmetric (94.7%)	Asymmetric (100%)
Femoral metal material	CoCr (99.8%)	CoCr (100%)	CoCr (98.0%)	CoCr (100%)	CoCr (96.7%)	CoCr (100%)
Tibial metal material	CoCr (76.5%)	Titanium (99.5%)	Titanium (56.2%)	CoCr (99.8%)	Titanium (100%)	Titanium (100%)
Insert polyethylene material	UHMWPE (68.6%)	UHMWPE (39.8%)	UHMWPE (47.2%)	XLPE+AOX (62.7%)	UHMWPE (50.6%)	XLPE+AOX (100%)
Patella resurfaced	No (56.8%)	No (79.2%)	No (54.1%)	No (84.1%)	Yes (71.8%)	No (62.5%)
Femoral stem	No (100%)	No (100%)	Yes (59.7%)	No (96.8%)	No (100%)	No (100%)
Tibial stem	No (98.1%)	No (100%)	No (97.1%)	No (99.4%)	No (96.9%)	No (95.0%)
Insert thickness (mm)	10.30 ± 1.40	10.18 ± 1.40	11.19 ± 1.71	9.57 ± 2.16	11.31 ± 1.50	10.82 ± 1.18

Table F.11: Question B cluster characterization (k = 6).

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Femoral AP/ML ratio	0.97 ± 0.08	1.05 ± 0.08	0.95 ± 0.12	0.92 ± 0.02	0.83 ± 0.06	0.79 ± 0.03
Tibial AP/ML ratio	0.66 ± 0.02	0.67 ± 0.01	0.68 ± 0.03	0.66 ± 0.01	0.71 ± 0.01	0.71 ± 0.00
Demographics						
Sex (% male)	37.6%	50.1%*	32.7%	46.6%	40.6%	40.6%
Submitting province (top)	ON (64.5%)	ON (47.1%)	ON (38.6%)	AB (58.4%)	ON (39.8%)	ON (45.2%)
Diagnosis (% OA)	98.9%	99.3%	95.0%	97.8%	98.9%	98.6%
Age at surgery (years)	69.68 ± 8.51	66.46 ± 8.28	68.06 ± 9.80	67.88 ± 9.16	68.63 ± 8.54	68.94 ± 8.59
Fiscal year	2020.75 ± 1.48	2021.50 ± 1.40	2021.15 ± 1.56	2020.84 ± 1.41	2020.77 ± 1.48	2021.69 ± 1.33

Table F.12: Question A (manufacturer/model + design features) cluster associations.

Variable	Test	p-value	Effect size	Input to clustering?
Insert mobility	χ^2	< 0.001	V = 1.00	Yes

Table F.12: Question A (manufacturer/model + design features) cluster associations.

Variable	**Test**	**p-value**	**Effect size**	**Input to clustering?**
Tibial symmetry	χ^2	< 0.001	$V = 1.00$	Yes
Femoral model	χ^2	< 0.001	$V = 0.83$	Yes
Tibial fixation	χ^2	< 0.001	$V = 0.73$	Yes
Tibial AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.75$	No
Femoral AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.67$	No
Insert stability	χ^2	< 0.001	$V = 0.57$	Yes
Insert polyethylene material	χ^2	< 0.001	$V = 0.48$	Yes
Tibial metal material	χ^2	< 0.001	$V = 0.46$	Yes
Submitting province	χ^2	< 0.001	$V = 0.26$	No
Patella resurfaced	χ^2	< 0.001	$V = 0.24$	Yes
Femoral metal material	χ^2	< 0.001	$V = 0.22$	Yes
Insert thickness	ANOVA	< 0.001	$\eta^2 = 0.085$	Yes
Diagnosis	χ^2	< 0.001	$V = 0.08$	No
Femoral stem	χ^2	< 0.001	$V = 0.08$	Yes
Fiscal year	ANOVA	< 0.001	$\eta^2 = 0.038$	No
Tibial stem	χ^2	< 0.001	$V = 0.12$	Yes
Sex	χ^2	< 0.001	$V = 0.03$	No
Age at surgery	ANOVA	< 0.001	$\eta^2 = 0.006$	No

Abbreviations: χ^2 = Pearson's chi-squared test of independence; ANOVA = one-way analysis of variance.

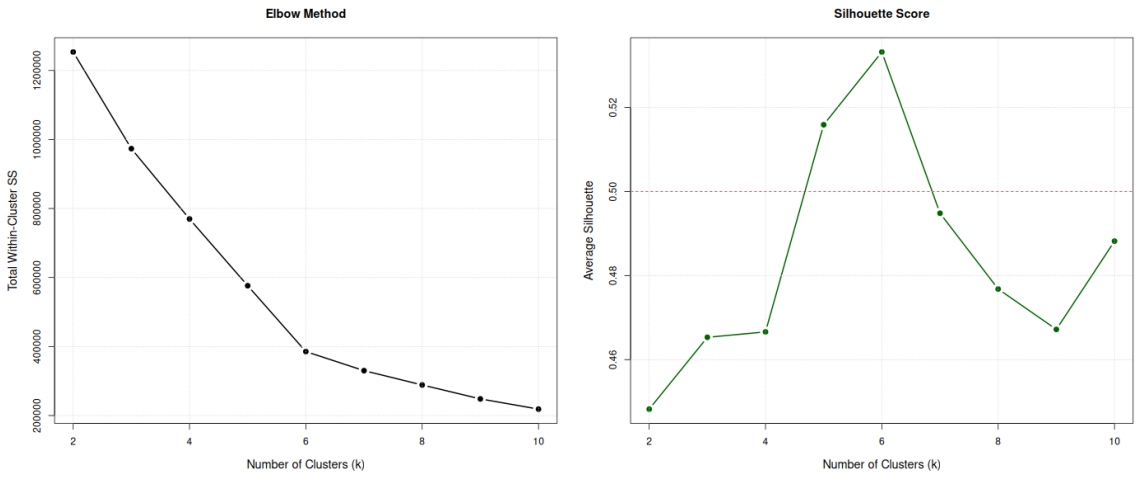


Figure F.5: Question A: silhouette and within-cluster sum of squares across candidate k, full dataset FAMD + k-means.

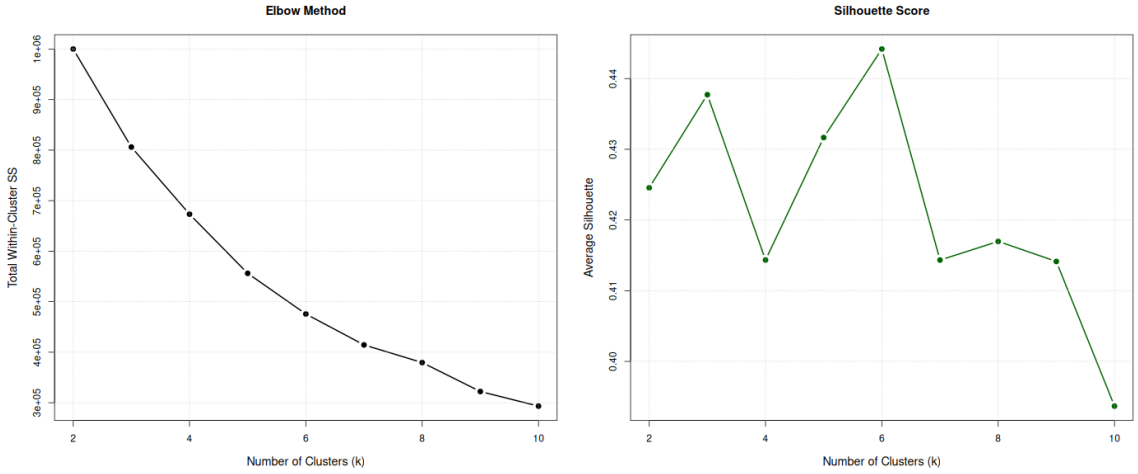


Figure F.6: Question B: silhouette and within-cluster sum of squares across candidate k, full dataset FAMD + k-means.

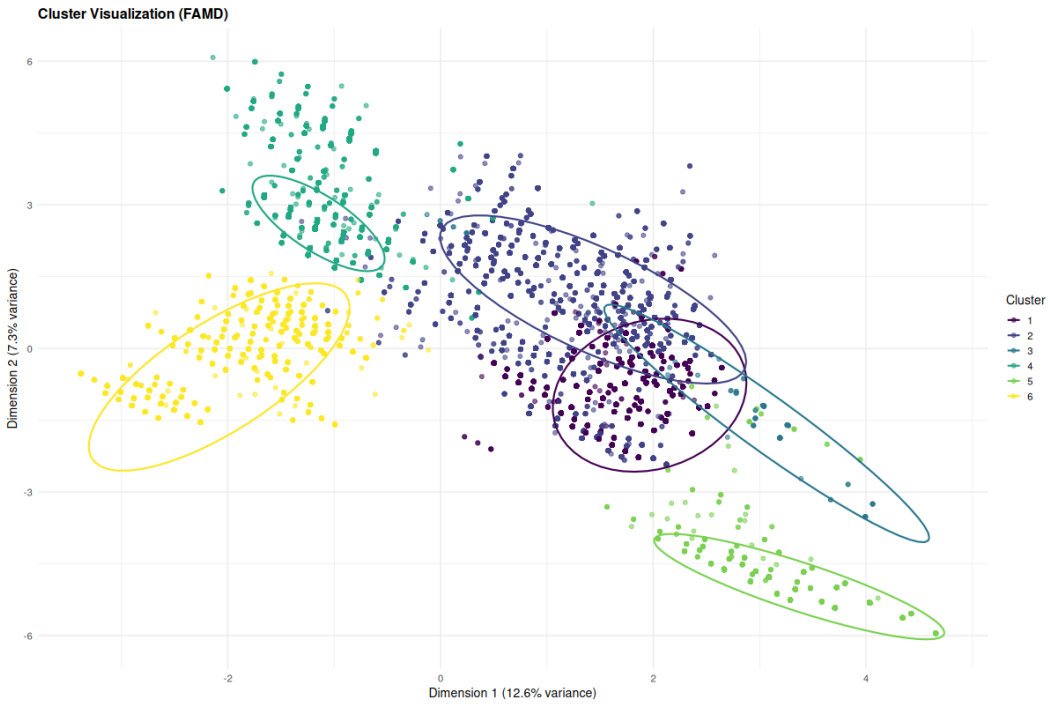


Figure F.7: Question A: six-cluster solution visualized on the first two FAMD dimensions, full dataset (n = 177,190).

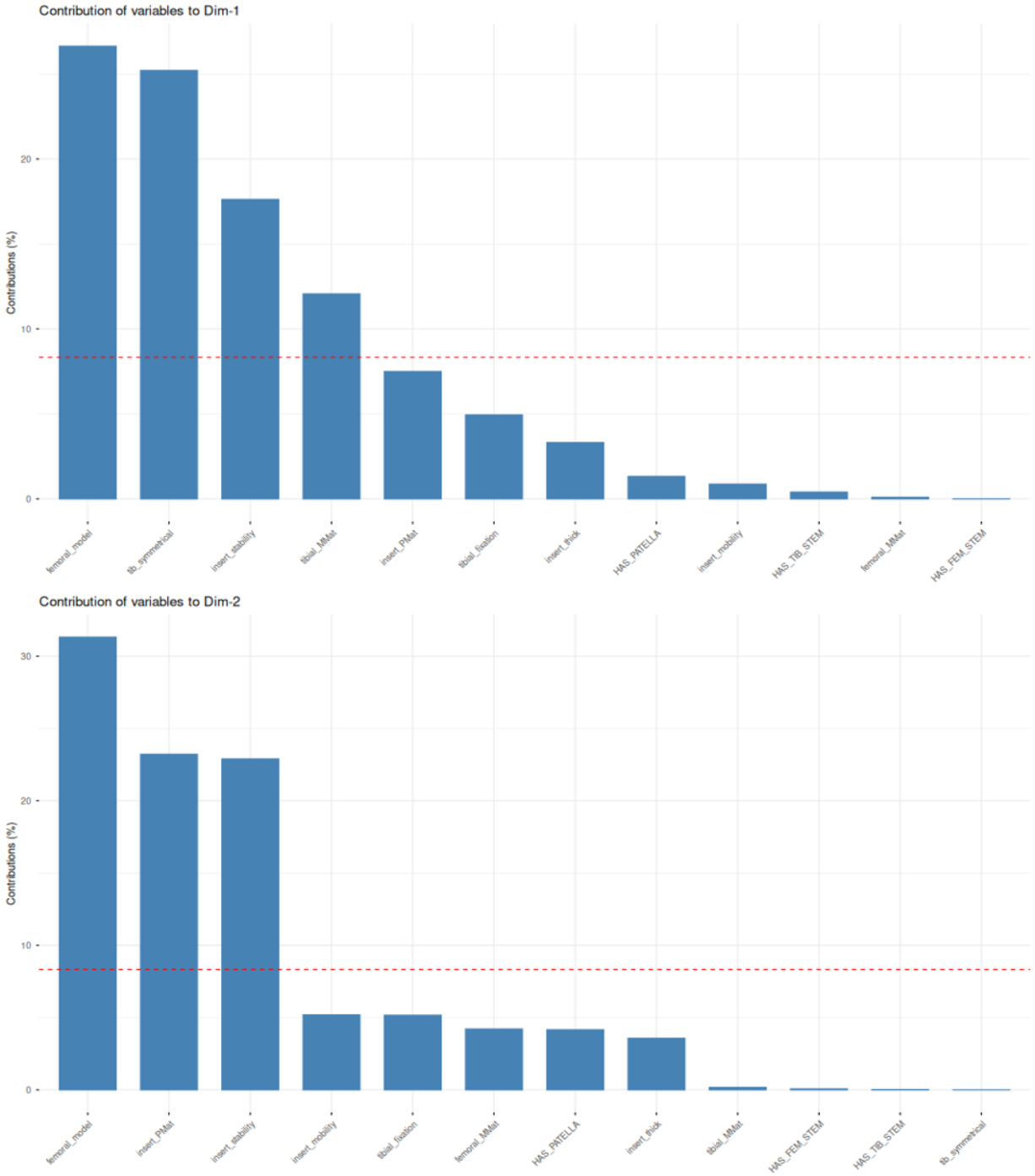


Figure F.8: Question A: six-cluster solution contributions to the first two FAMD dimensions, full dataset (n = 177,190). Red line indicates contributions of at least 8%.

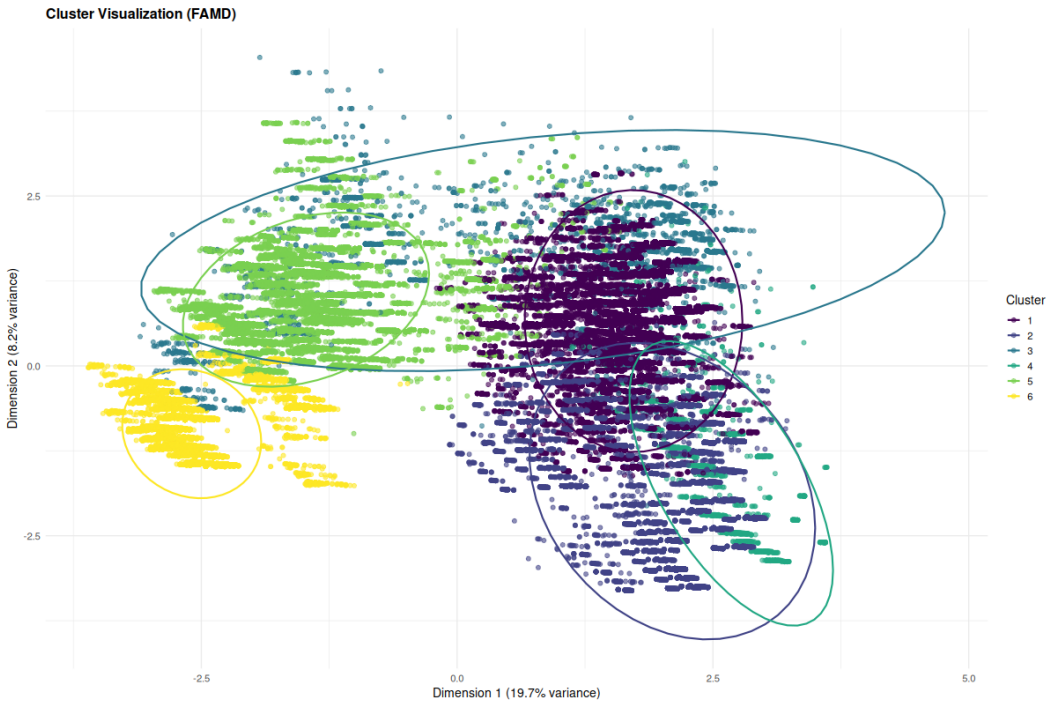


Figure F.9: Question B: six-cluster solution visualized on the first two FAMD dimensions, full dataset (n = 177,190).

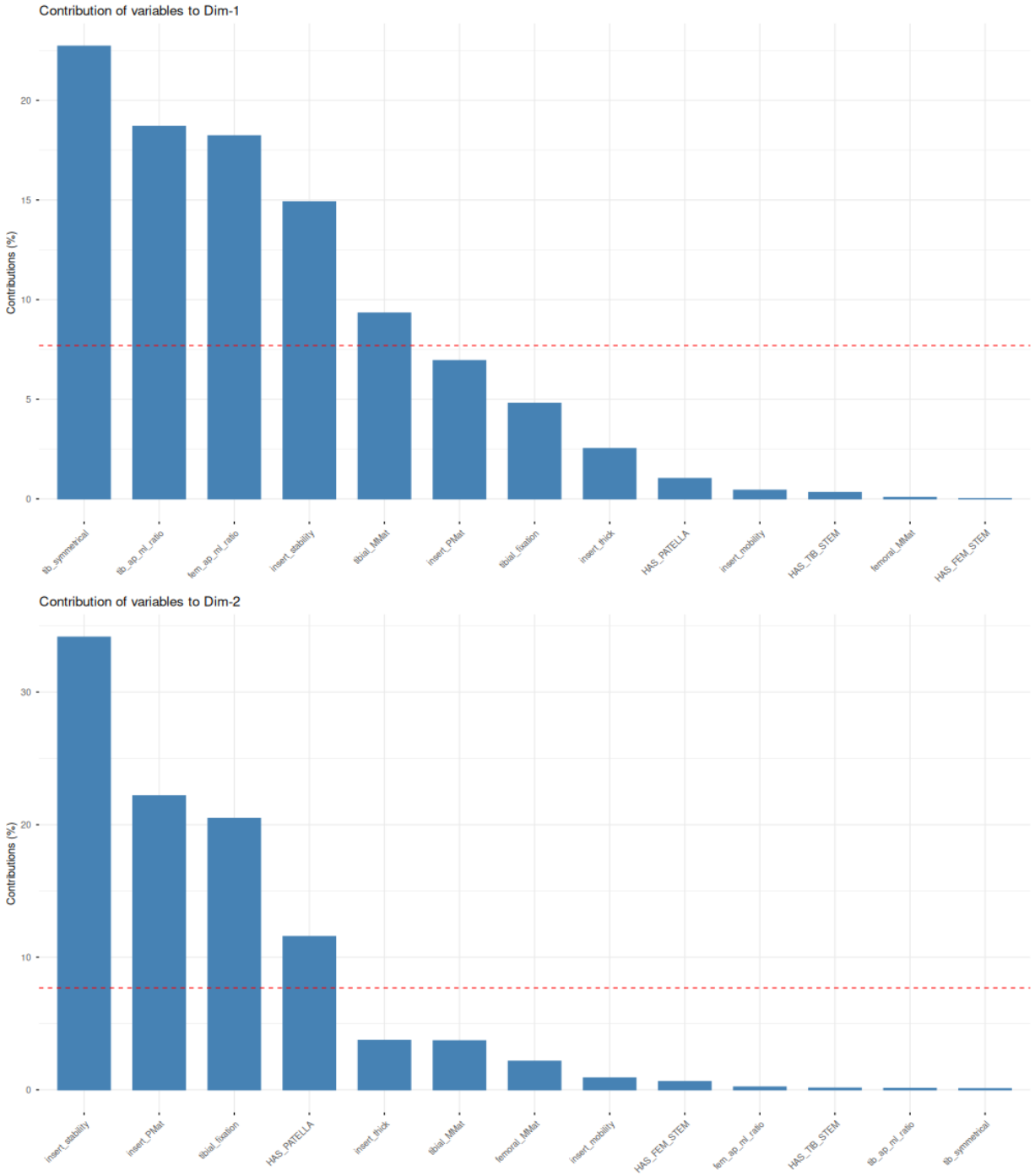


Figure F.10: Question B: six-cluster solution contributions to the first two FAMD dimensions, full dataset (n = 177,190).

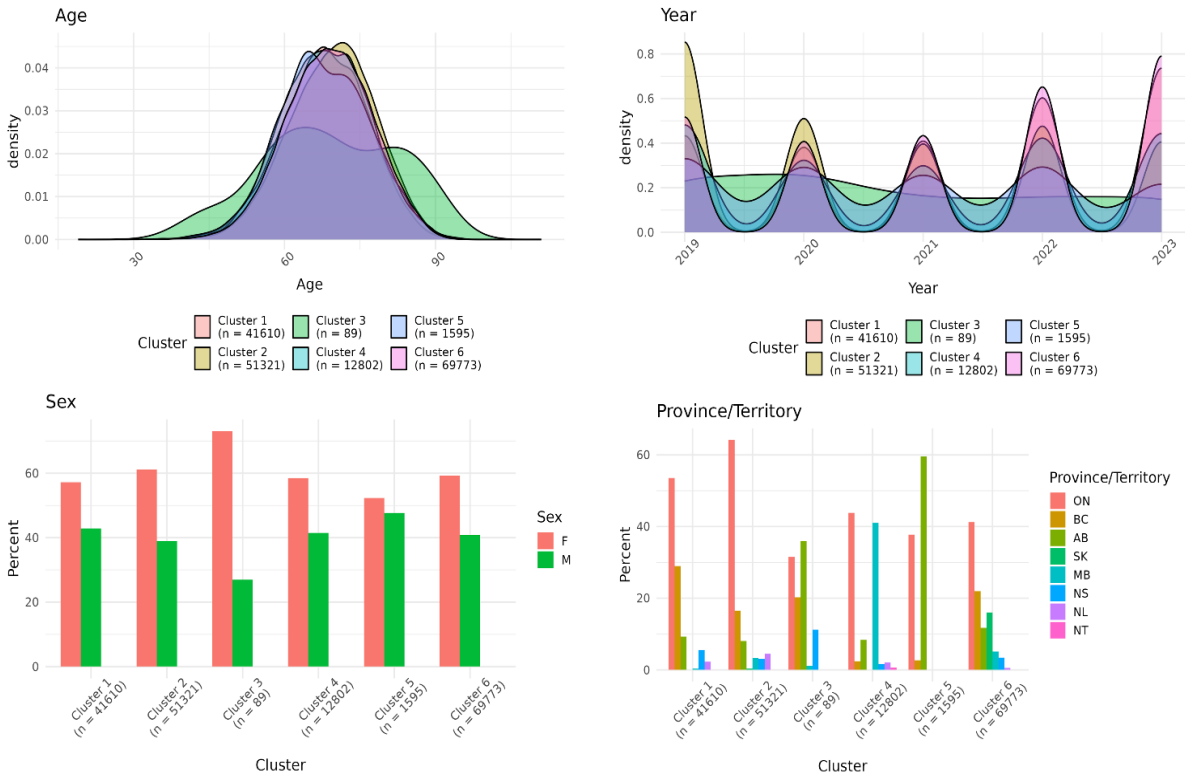


Figure F.11: Question A cluster demographic variables (age, fiscal year, sex, province).



Figure F.12: Question A cluster categorical and binary variable distributions.

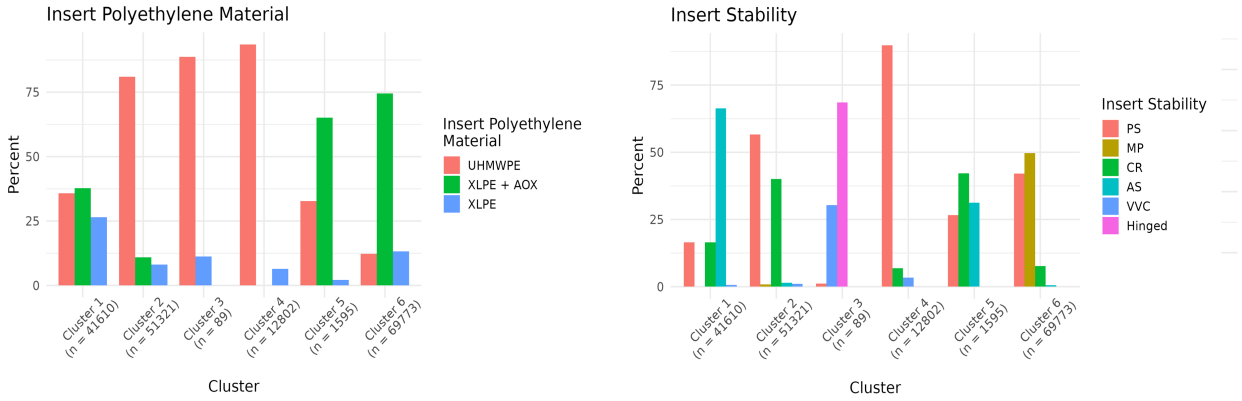


Figure F.13: Question A cluster categorical and binary variable distributions (continued).

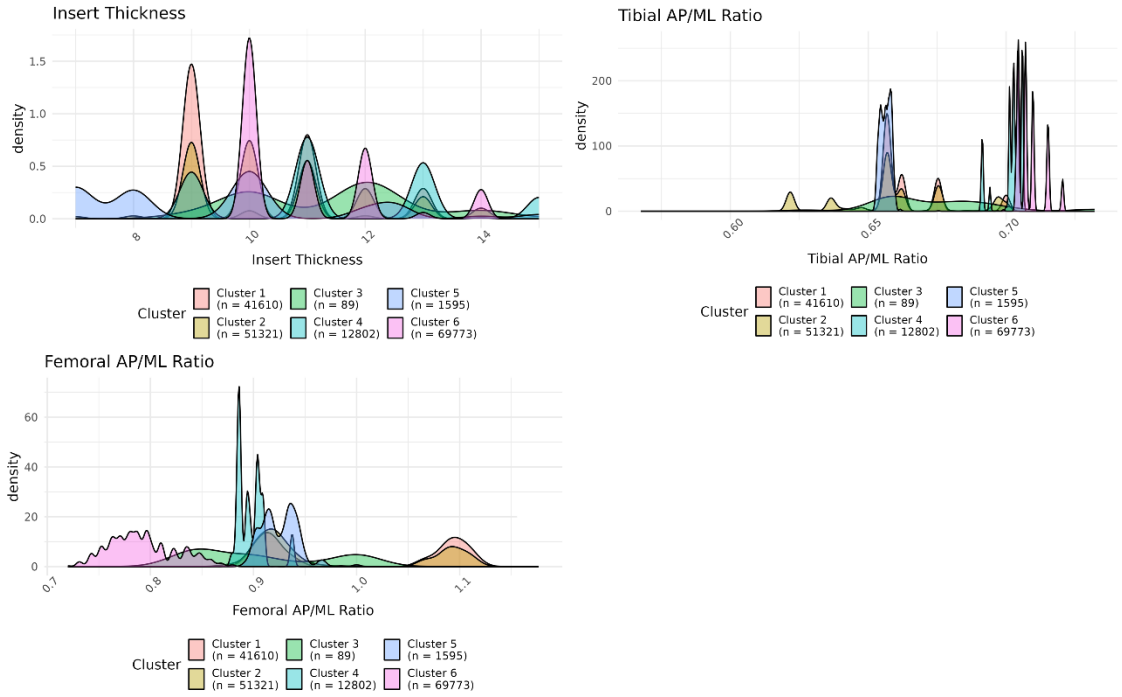


Figure F.14: Question A cluster numerical variable density plots.

Table F.13: Question A: multinomial logistic regression; reference cluster = Cluster 6, reference sex = Female, reference year = 2021. Model fit: McFadden pseudo-R^2 = 0.018, multiclass AUROC = 0.575.

Cluster (vs. Cluster 6)	Term	OR	95% CI	p-value
Cluster 1	Age at surgery	0.98	0.98-0.99	< 0.001
	Male sex	1.09	1.06-1.12	< 0.001
	Fiscal year 2019 (vs. 2021)	0.88	0.84-0.92	< 0.001
	Fiscal year 2020 (vs. 2021)	0.98	0.94-1.02	0.366
	Fiscal year 2022 (vs. 2021)	0.98	0.95-1.02	0.394
	Fiscal year 2023 (vs. 2021)	1.00	0.96-1.03	0.841
Cluster 2	Age at surgery	1.01	1.01-1.01	< 0.001
	Male sex	0.92	0.90-0.94	< 0.001
	Fiscal year 2019 (vs. 2021)	1.82	1.76-1.89	< 0.001
	Fiscal year 2020 (vs. 2021)	1.39	1.33-1.44	< 0.001
	Fiscal year 2022 (vs. 2021)	0.80	0.77-0.83	< 0.001
	Fiscal year 2023 (vs. 2021)	0.56	0.54-0.58	< 0.001
Cluster 3	Age at surgery	1.01	1.00-1.01	< 0.001
	Male sex	0.53	0.33-0.85	0.008
	Fiscal year 2019 (vs. 2021)	1.48	1.02-2.17	0.040
	Fiscal year 2020 (vs. 2021)	1.98	1.36-2.88	< 0.001
	Fiscal year 2022 (vs. 2021)	0.72	0.47-1.10	0.125
	Fiscal year 2023 (vs. 2021)	0.63	0.41-0.96	0.031
Cluster 4	Age at surgery	1.00	0.99-1.00	< 0.001
	Male sex	1.03	0.99-1.07	0.141
	Fiscal year 2019 (vs. 2021)	1.35	1.27-1.43	< 0.001
	Fiscal year 2020 (vs. 2021)	1.15	1.07-1.23	< 0.001
	Fiscal year 2022 (vs. 2021)	0.94	0.89-1.00	0.065
	Fiscal year 2023 (vs. 2021)	0.82	0.77-0.87	< 0.001
Cluster 5	Age at surgery	0.99	0.98-0.99	< 0.001

Table F.13: Question A: multinomial logistic regression; reference cluster = Cluster 6, reference sex = Female, reference year = 2021. Model fit: McFadden pseudo-R^2 = 0.018, multiclass AUROC = 0.575.

Cluster (vs. Cluster 6)	Term	OR	95% CI	p-value
	Male sex	1.32	1.20-1.46	< 0.001
	Fiscal year 2019 (vs. 2021)	1.08	0.93-1.26	0.334
	Fiscal year 2020 (vs. 2021)	1.20	1.03-1.41	0.022
	Fiscal year 2022 (vs. 2021)	0.76	0.65-0.90	< 0.001
	Fiscal year 2023 (vs. 2021)	0.47	0.39-0.55	< 0.001

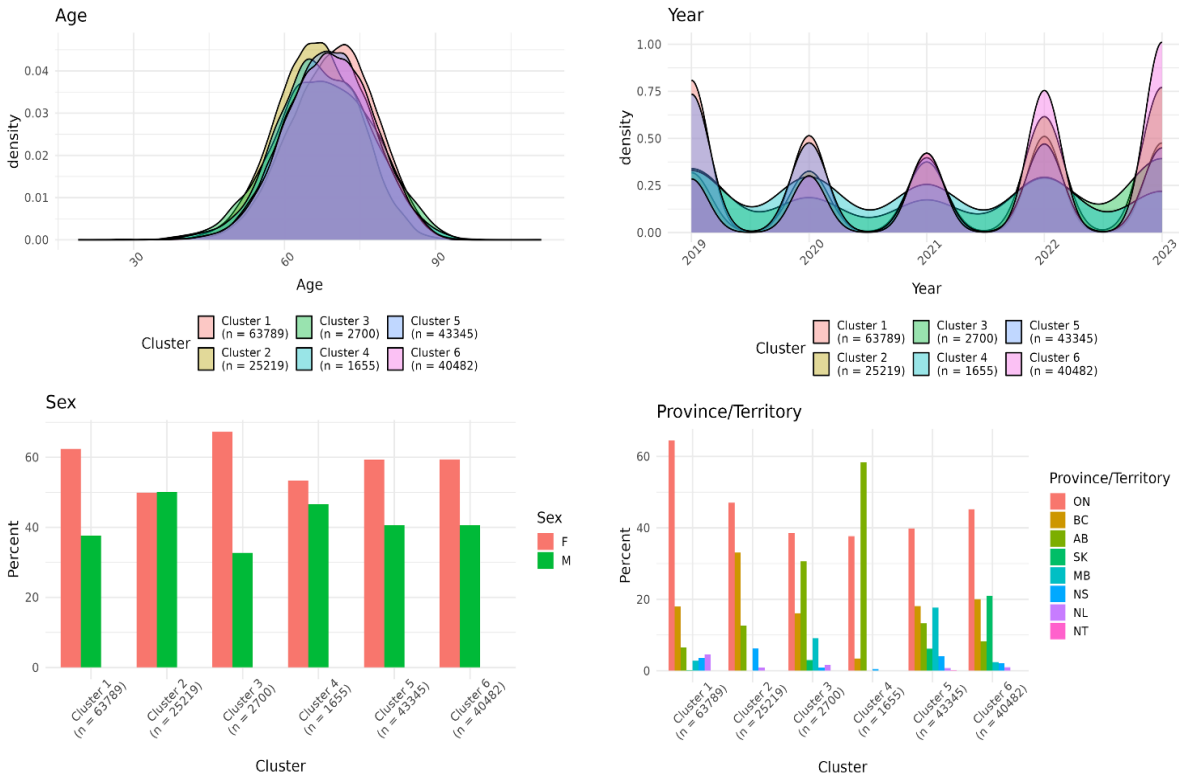


Figure F.15: Question B cluster demographic variables (age, fiscal year, sex, province).

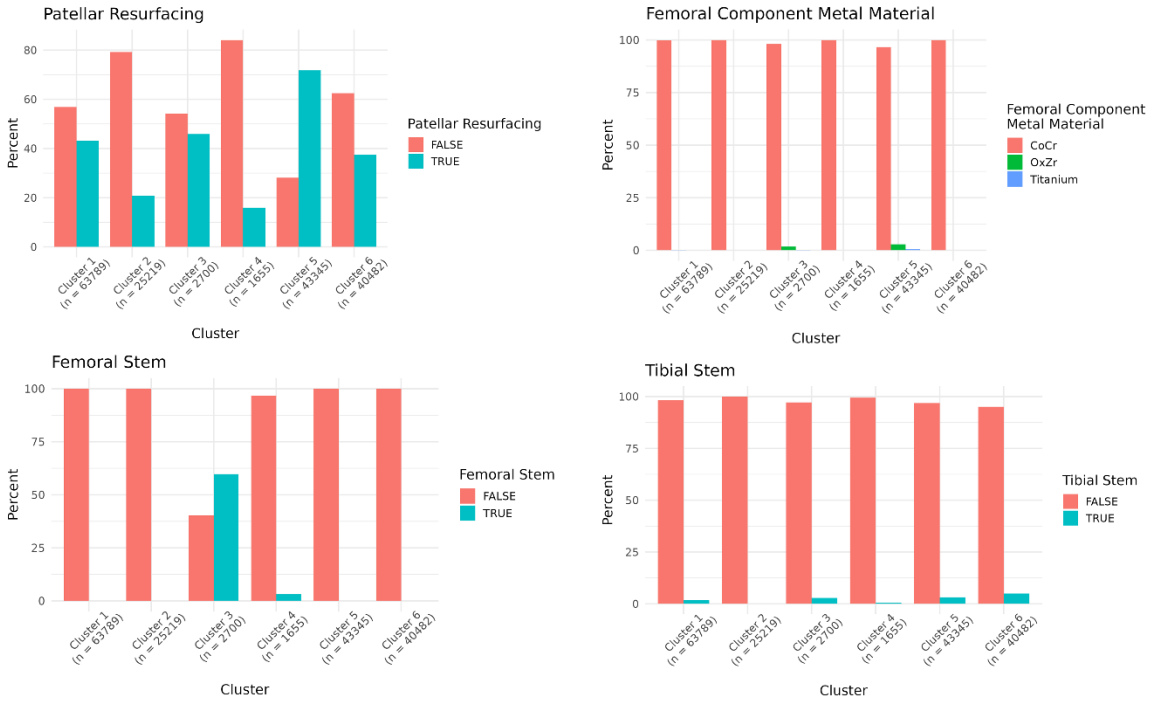


Figure F.16: Question B cluster categorical and binary variable distributions.

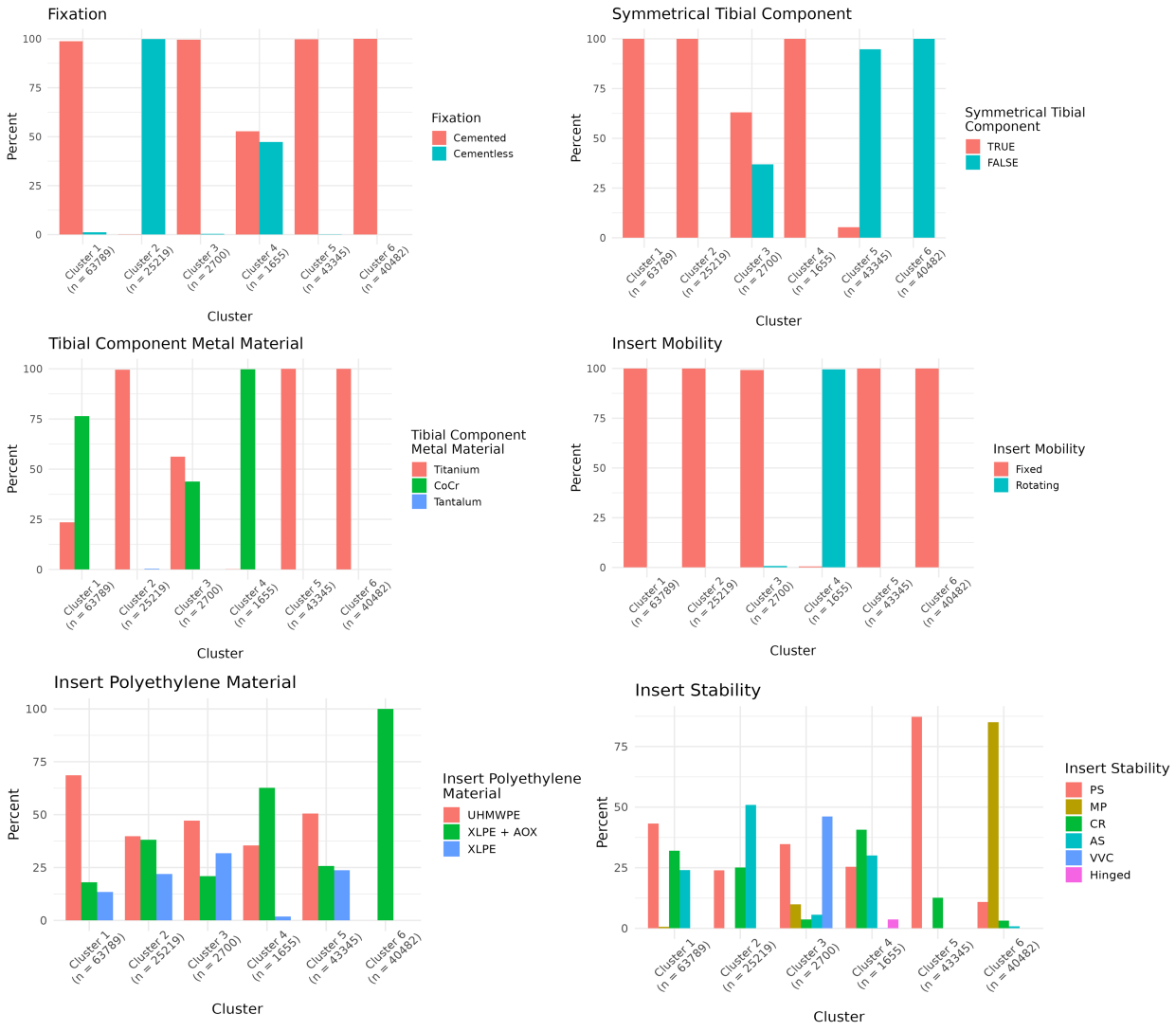


Figure F.16: Question B cluster categorical and binary variable distributions (continued).

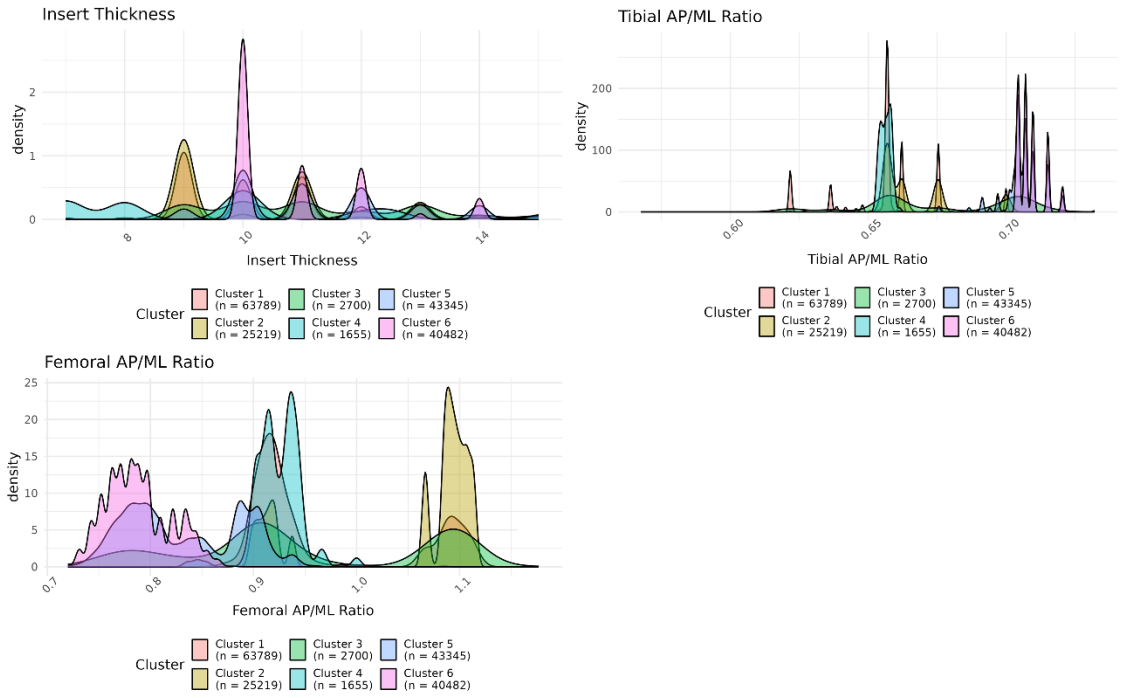


Figure F.17: Question B cluster numerical variable density plots.

Table F.14: Question B (functional configuration only) cluster associations.

Variable	**Test**	**p-value**	**Effect size**	**Input to clustering?**
Tibial fixation	χ^2	< 0.001	$V = 0.97$	Yes
Insert mobility	χ^2	< 0.001	$V = 0.99$	Yes
Tibial symmetry	χ^2	< 0.001	$V = 0.97$	Yes
Femoral stem	χ^2	< 0.001	$V = 0.76$	Yes
Tibial AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.75$	Yes
Femoral AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.67$	Yes
Femoral model	χ^2	< 0.001	$V = 0.60$	No
Tibial metal material	χ^2	< 0.001	$V = 0.58$	Yes
Insert stability	χ^2	< 0.001	$V = 0.56$	Yes
Insert polyethylene material	χ^2	< 0.001	$V = 0.48$	Yes
Patella resurfaced	χ^2	< 0.001	$V = 0.34$	Yes
Submitting province	χ^2	< 0.001	$V = 0.23$	No
Insert thickness	ANOVA	< 0.001	$\eta^2 = 0.095$	Yes
Fiscal year	ANOVA	< 0.001	$\eta^2 = 0.076$	No
Sex	χ^2	< 0.001	$V = 0.08$	No
Tibial stem	χ^2	< 0.001	$V = 0.10$	Yes
Femoral metal material	χ^2	< 0.001	$V = 0.11$	Yes
Age at surgery	ANOVA	< 0.001	$\eta^2 = 0.015$	No
Diagnosis	χ^2	< 0.001	$V = 0.04$	No

Abbreviations: χ^2 = Pearson's chi-squared test of independence; ANOVA = one-way analysis of variance.

Table F.15: Question B: pooled multinomial logistic regression; reference cluster = Cluster 1, reference sex = Female, reference year = 2021. Model fit: McFadden pseudo-R^2 = 0.036, multiclass AUROC = 0.601.

Cluster (vs. Cluster 1)	**Term**	**OR**	**95% CI**	**p-value**
Cluster 2	Age at surgery	0.95	0.95-0.95	< 0.001
	Male sex	1.71	1.66-1.76	< 0.001
	Fiscal year 2019 (vs. 2021)	0.42	0.40-0.45	< 0.001
	Fiscal year 2020 (vs. 2021)	0.68	0.65-0.72	< 0.001
	Fiscal year 2022 (vs. 2021)	1.38	1.31-1.44	< 0.001
	Fiscal year 2023 (vs. 2021)	1.89	1.80-1.98	< 0.001
Cluster 3	Age at surgery	0.98	0.97-0.98	< 0.001
	Male sex	0.82	0.75-0.89	< 0.001
	Fiscal year 2019 (vs. 2021)	1.01	0.88-1.15	0.931
	Fiscal year 2020 (vs. 2021)	0.87	0.74-1.01	0.059
	Fiscal year 2022 (vs. 2021)	1.39	1.21-1.60	< 0.001
	Fiscal year 2023 (vs. 2021)	2.05	1.80-2.34	< 0.001
Cluster 4	Age at surgery	0.98	0.97-0.98	< 0.001
	Male sex	1.46	1.32-1.61	< 0.001
	Fiscal year 2019 (vs. 2021)	0.66	0.57-0.77	< 0.001
	Fiscal year 2020 (vs. 2021)	0.93	0.79-1.08	0.340
	Fiscal year 2022 (vs. 2021)	0.96	0.82-1.12	0.604
	Fiscal year 2023 (vs. 2021)	0.78	0.66-0.92	< 0.001
Cluster 5	Age at surgery	0.98	0.98-0.99	< 0.001
	Male sex	1.14	1.11-1.17	< 0.001
	Fiscal year 2019 (vs. 2021)	0.95	0.92-0.99	0.015
	Fiscal year 2020 (vs. 2021)	0.97	0.93-1.01	0.168
	Fiscal year 2022 (vs. 2021)	0.98	0.94-1.03	0.422
	Fiscal year 2023 (vs. 2021)	1.01	0.97-1.06	0.511
Cluster 6	Age at surgery	0.98	0.98-0.99	< 0.001

Table F.15: Question B: pooled multinomial logistic regression; reference cluster = Cluster 1, reference sex = Female, reference year = 2021. Model fit: McFadden pseudo-R^2 = 0.036, multiclass AUROC = 0.601.

Cluster (vs. Cluster 1)	Term	OR	95% CI	p-value
	Male sex	1.15	1.12-1.18	< 0.001
	Fiscal year 2019 (vs. 2021)	0.35	0.33-0.36	< 0.001
	Fiscal year 2020 (vs. 2021)	0.58	0.55-0.61	< 0.001
	Fiscal year 2022 (vs. 2021)	1.49	1.43-1.55	< 0.001
	Fiscal year 2023 (vs. 2021)	2.15	2.07-2.24	< 0.001

F.6 Sex-Stratified EDA and Clustering

EDA and clustering were additionally repeated separately for male and female procedures as a sensitivity analysis. K-Prototypes was the best-performing method on both sex-stratified test samples and was carried forward to the full male (n = 70,804) and female (n = 101,123) sub-cohorts, yielding the three- and four-cluster solutions summarized in Results (Sex-Disaggregated Analysis).

To enable direct comparisons between clustering solutions for the male and female cohorts, the clustering solution that performed best across both cohorts was chosen (Table F.16). For females, the best model was FAMD with k-means, though k-prototypes had a near-identical mean Jaccard coefficient. In the male cohort, the k-prototypes method had a notably higher mean Jaccard coefficient. Taken together, the k-prototypes method was chosen for the full-dataset runs.

Table F.16: Cross-method comparison, 10,000-procedure test samples. Silhouette and Jaccard computed on Gower distance (categorical-only for LCA; mixed for other methods). LCA solutions show comparatively high silhouette but low bootstrap stability across both specifications and were thus not selected as the primary method.

Specification	Method	k	Mean silhouette	Mean Jaccard
Female	K-Prototypes	4	0.276	0.696
Female	KAMILA	4	0.032	0.411
Female	FAMD + k-means	9	0.363	0.700
Female	LCA	4	0.333	0.213
Male	K-Prototypes	4	0.398	0.778
Male	KAMILA	4	0.042	0.662
Male	FAMD + k-means	9	0.374	0.771
Male	LCA	4	0.445	0.330

For the final full sex-disaggregated dataset k-prototypes solutions, silhouette width was

evaluated across k = 2-10 (Figs. F.18 and F.19). The optimal solution selected for the male cohort was k = 3 as the silhouette-maximizing, minimum-cluster-size-compliant solution, and k = 4 for the female cohort.

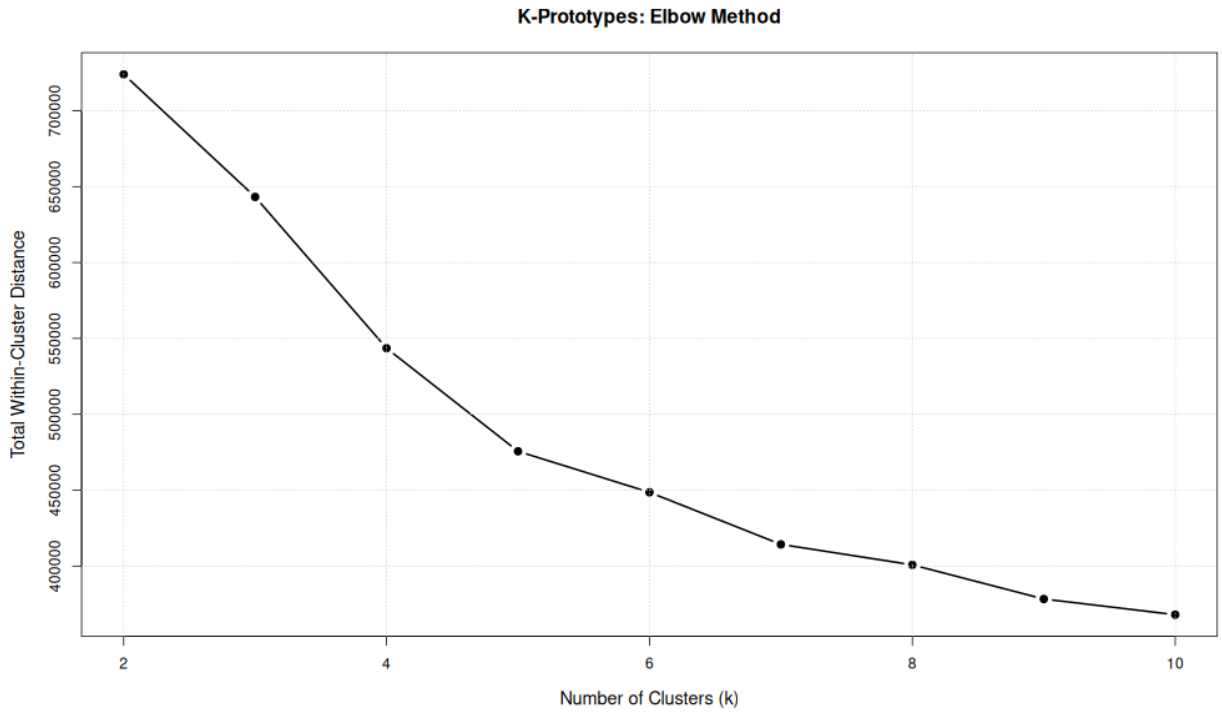


Figure F.18: Question B Female Cohort: silhouette and within-cluster sum of squares across candidate k, full male dataset k-prototypes.

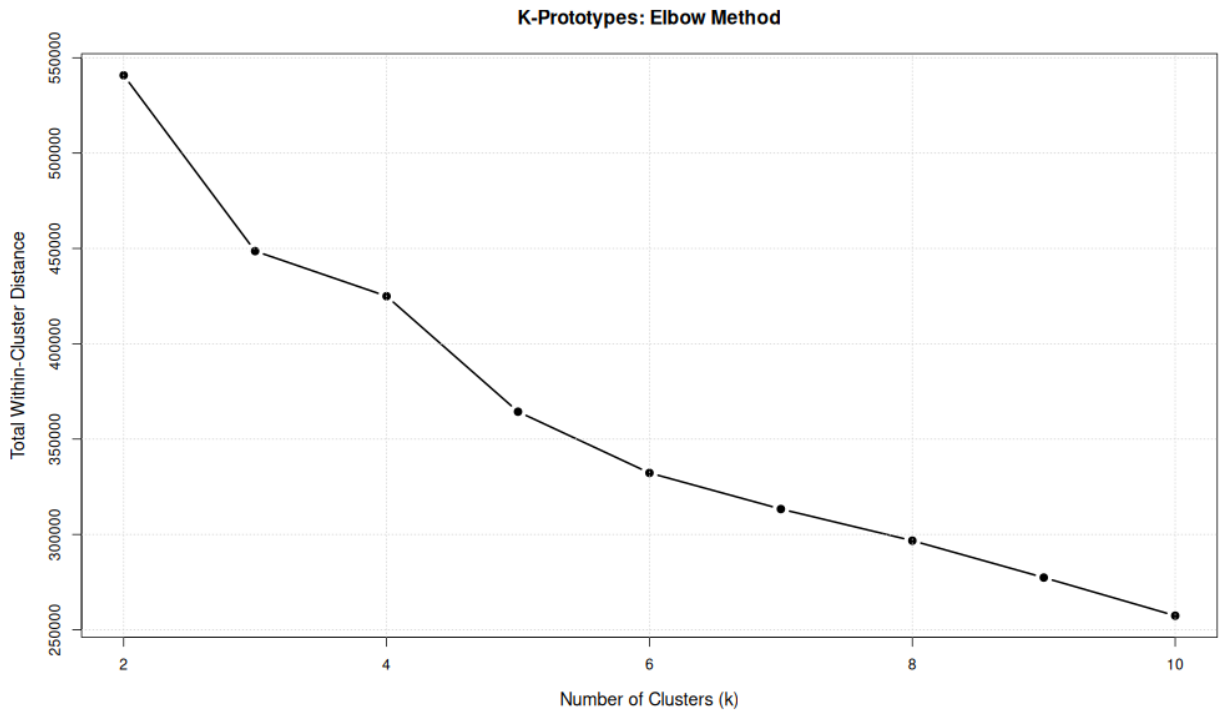


Figure F.19: Question B Male Cohort: silhouette and within-cluster sum of squares across candidate k, full male dataset k-prototypes.

F.6.1 Female

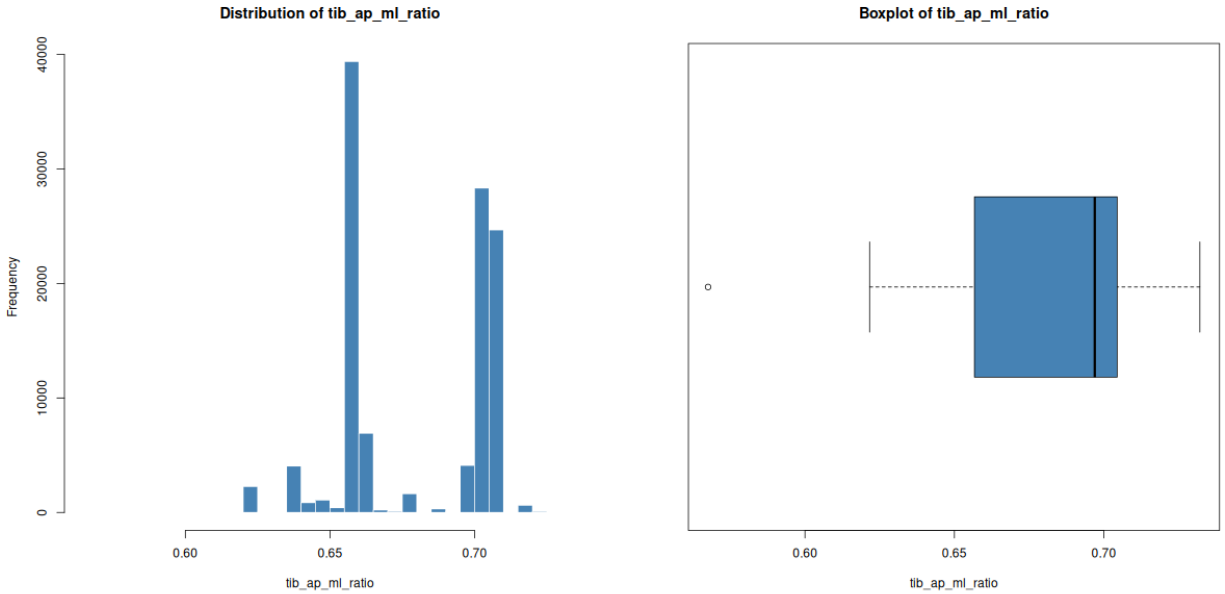


Figure F.20: Tibial AP/ML ratio distribution for the female cohort. AP = anteroposterior, ML = mediolateral.

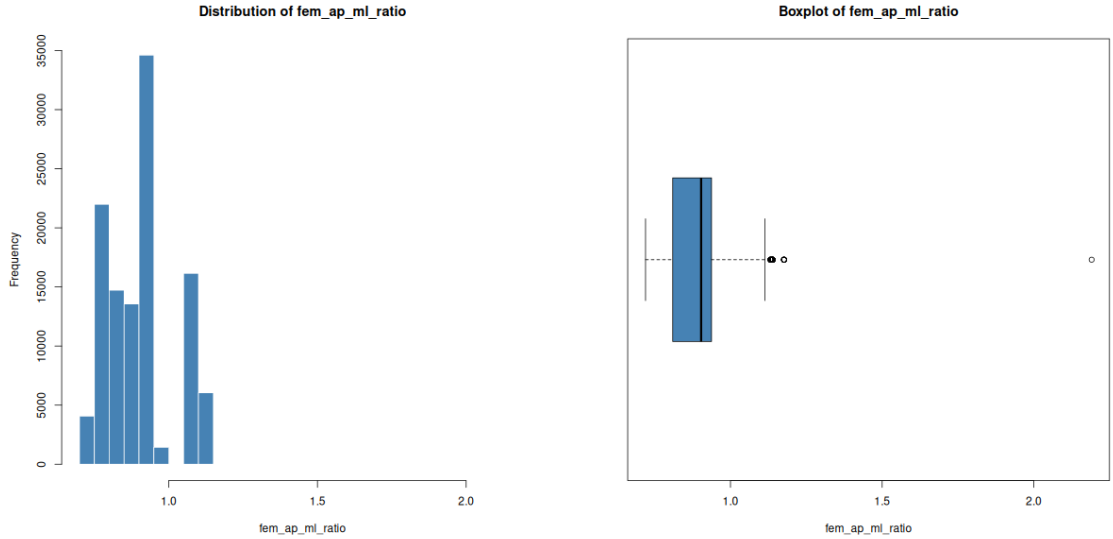


Figure F.21: Femoral AP/ML ratio distribution for the female cohort. AP = anteroposterior, ML = mediolateral.

Table F.17: Question B, female cohort cluster characterization (k = 4).

Variable	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
n (%)	23,547 (23.3%)	28,688 (28.4%)	23,197 (22.9%)	25,691 (25.4%)
Implant Characteristics				
Tibial fixation	Cemented (89.3%)	Cemented (66.3%)	Cemented (99.8%)	Cemented (100%)
Insert stability	PS (59.2%)	CR (44.7%)	PS (89.7%)	MP (79.4%)
Insert mobility	Fixed (98.4%)	Fixed (98.3%)	Fixed (100%)	Fixed (100%)
Tibial symmetry	Symmetric (100%)	Symmetric (99.5%)	Asymmetric (95.0%)	Asymmetric (100%)
Femoral metal material	CoCr (99.6%)	CoCr (99.1%)	CoCr (96.7%)	CoCr (99.9%)

Table F.17: Question B, female cohort cluster characterization (k = 4).

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Tibial metal material	CoCr (83.8%)	Titanium (59.4%)	Titanium (100%)	Titanium (100%)
Insert polyethylene material	UHMWPE (59.7%)	UHMWPE (60.8%)	UHMWPE (56.8%)	XLPE+AOX (96.1%)
Patella resurfaced	Yes (72.9%)	No (90.4%)	Yes (81.1%)	No (63.2%)
Femoral stem	No (98.3%)	No (99.2%)	No (99.2%)	No (99.0%)
Tibial stem	No (97.7%)	No (99.3%)	No (96.1%)	No (95.1%)
Insert thickness (mm)	10.25 ± 1.48	10.27 ± 1.37	11.27 ± 1.51	10.87 ± 1.19
Femoral AP/ML ratio	1.00 ± 0.08	0.96 ± 0.08	0.83 ± 0.06	0.79 ± 0.04
Tibial AP/ML ratio	0.66 ± 0.01	0.66 ± 0.02	0.70 ± 0.00	0.71 ± 0.00
Demographics				
Submitting province (top)	ON (57.5%)	ON (61.8%)	ON (40.6%)	ON (43.4%)
Diagnosis (% OA)	98.8%	98.9%	98.8%	98.6%
Age at surgery (years)	69.13 ± 8.70	68.31 ± 8.73	68.60 ± 8.68	68.83 ± 8.75
Fiscal year	2020.88 ± 1.49	2021.00 ± 1.50	2020.75 ± 1.49	2021.62 ± 1.37

Table F.18: Question B, female cohort cluster associations.

Variable	Test	p-value	Effect size	Input to clustering?
Tibial symmetry	χ^2	< 0.001	V = 0.98	Yes

Table F.18: Question B, female cohort cluster associations.

Variable	Test	p-value	Effect size	Input to clustering?
Tibial AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.86$	Yes
Insert stability	χ^2	< 0.001	V = 0.61	Yes
Femoral model	χ^2	< 0.001	V = 0.64	No
Femoral AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.64$	Yes
Patella resurfaced	χ^2	< 0.001	V = 0.58	Yes
Tibial metal material	χ^2	< 0.001	V = 0.52	Yes
Insert polyethylene material	χ^2	< 0.001	V = 0.45	Yes
Tibial fixation	χ^2	< 0.001	V = 0.44	Yes
Submitting province	χ^2	< 0.001	V = 0.28	No
Insert thickness	ANOVA	< 0.001	$\eta^2 = 0.085$	Yes
Fiscal year	ANOVA	< 0.001	$\eta^2 = 0.049$	No
Tibial stem	χ^2	< 0.001	V = 0.10	Yes
Femoral metal material	χ^2	< 0.001	V = 0.10	Yes
Insert mobility	χ^2	< 0.001	V = 0.09	Yes
Femoral stem	χ^2	< 0.001	V = 0.04	Yes
Age at surgery	ANOVA	< 0.001	$\eta^2 = 0.001$	No
Diagnosis	χ^2	< 0.001	V = 0.01	No

Abbreviations: χ^2 = Pearson's chi-squared test of independence; ANOVA = one-way analysis of variance.

Table F.19: Female Question B multinomial logistic regression; reference cluster = Cluster 2, reference year = 2021. Model fit: McFadden R^2 = 0.0188, multiclass AUROC = 0.573.

Cluster (vs. Cluster 2)	Term	OR	95% CI	p-value
Cluster 1	Age at surgery	1.01	1.01-1.01	<0.001

Table F.19: Female Question B multinomial logistic regression; reference cluster = Cluster 2, reference year = 2021. Model fit: McFadden R^2 = 0.0188, multiclass AUROC = 0.573.

Cluster (vs. Cluster 2)	**Term**	**OR**	**95% CI**	**p-value**
Cluster 3	Fiscal year 2019 (vs. 2021)	1.1	1.04-1.16	<0.001
	Fiscal year 2020 (vs. 2021)	1.06	0.99-1.12	0.081
	Fiscal year 2022 (vs. 2021)	0.97	0.92-1.03	0.33
	Fiscal year 2023 (vs. 2021)	0.85	0.80-0.90	<0.001
	Age at surgery	1	1.00-1.01	<0.001
Cluster 4	Fiscal year 2019 (vs. 2021)	1.23	1.16-1.30	<0.001
	Fiscal year 2020 (vs. 2021)	1.11	1.04-1.18	<0.001
	Fiscal year 2022 (vs. 2021)	0.89	0.84-0.94	<0.001
	Fiscal year 2023 (vs. 2021)	0.78	0.75-0.83	<0.001
	Age at surgery	1	1.00-1.01	<0.001
	Fiscal year 2019 (vs. 2021)	0.51	0.48-0.54	<0.001
	Fiscal year 2020 (vs. 2021)	0.7	0.66-0.74	<0.001

Table F.19: Female Question B multinomial logistic regression; reference cluster = Cluster 2, reference year = 2021. Model fit: McFadden R^2 = 0.0188, multiclass AUROC = 0.573.

Cluster (vs. Cluster 2)	Term	OR	95% CI	p-value
	Fiscal year 2022 (vs. 2021)	1.33	1.25-1.40	<0.001
	Fiscal year 2023 (vs. 2021)	1.63	1.54-1.71	<0.001

F.6.2 Male

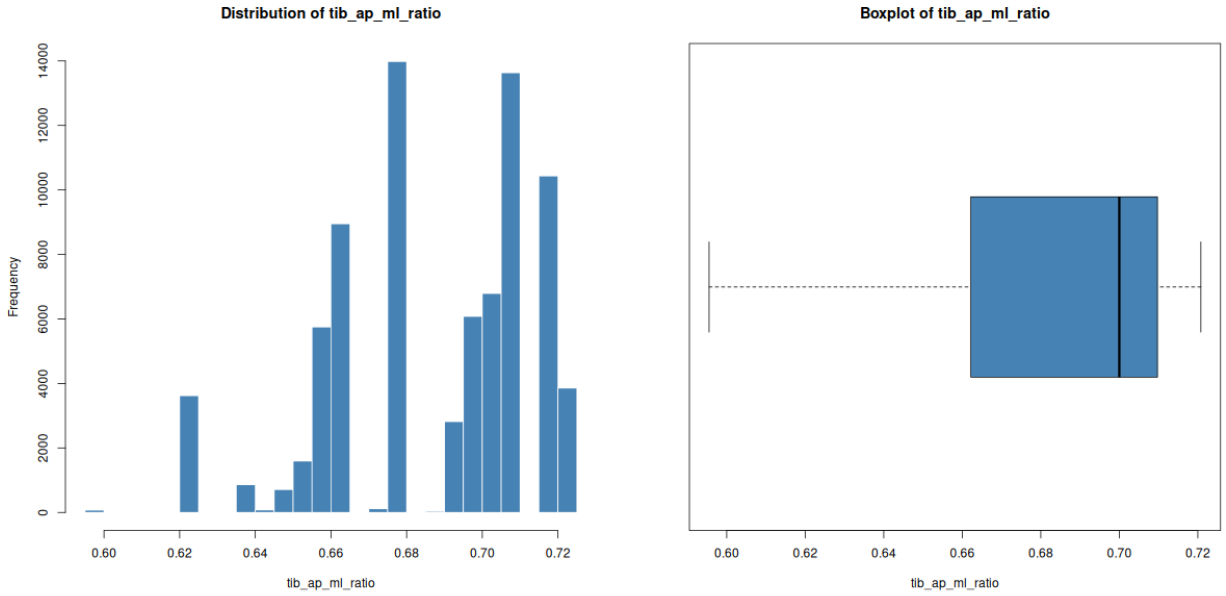


Figure F.22: Tibial AP/ML ratio distribution for the male cohort. AP = anteroposterior, ML = mediolateral

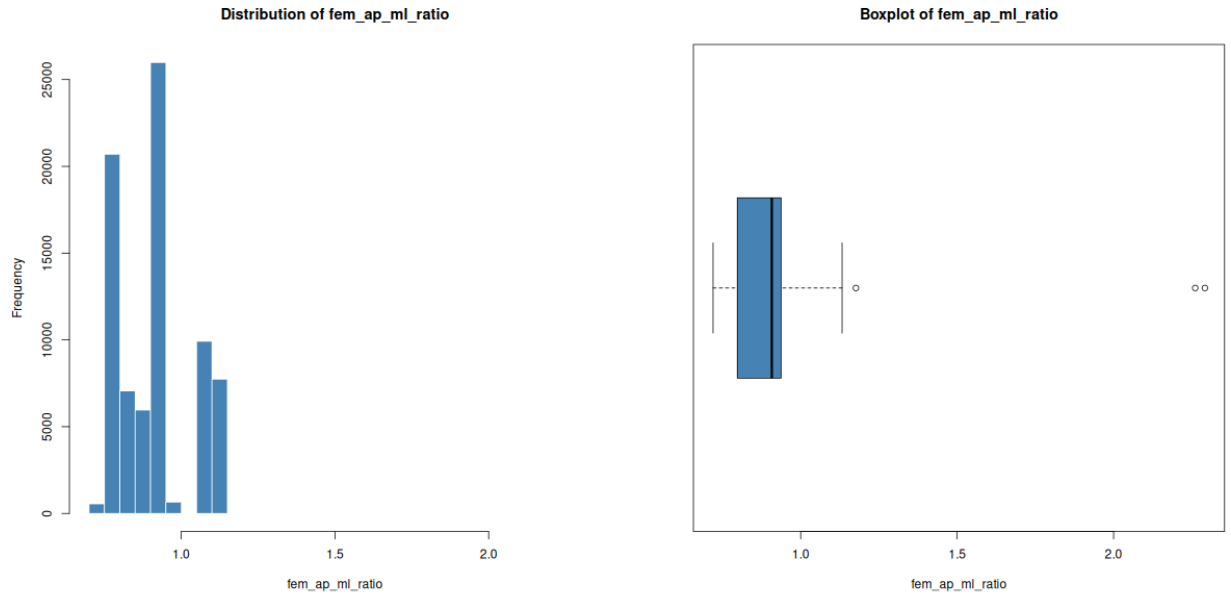


Figure F.23: Femoral AP/ML ratio distribution for the male cohort. AP = anteroposterior, ML = mediolateral

Table F.20: Question B, male cohort cluster characterization (k = 3).

Variable	**Cluster 1**	**Cluster 2**	**Cluster 3**
n (%)	12,432 (17.6%)	33,612 (47.5%)	24,760 (35.0%)
Implant Characteristics			
Tibial fixation	Cementless (99.3%)	Cemented (98.5%)	Cemented (98.0%)
Insert stability	AS (52.2%)	PS (50.7%)	PS (46.9%)
Insert mobility	Fixed (99.3%)	Fixed (100%)	Fixed (97.3%)
Tibial symmetry	Symmetric (99.8%)	Asymmetric (97.3%)	Symmetric (99.1%)
Femoral metal material	CoCr (100%)	CoCr (98.8%)	CoCr (99.9%)
Tibial metal material	Titanium (99.1%)	Titanium (99.8%)	CoCr (74.2%)

Table F.20: Question B, male cohort cluster characterization (k = 3).

Variable	**Cluster 1**	**Cluster 2**	**Cluster 3**
Insert polyethylene material	UHMWPE (42.4%)	XLPE+AOX (60.8%)	UHMWPE (69.2%)
Patella resurfaced	No (82.1%)	Yes (53.8%)	No (60.2%)
Femoral stem	No (100%)	No (99.4%)	No (98.7%)
Tibial stem	No (100%)	No (96.9%)	No (98.4%)
Insert thickness (mm)	10.20 ± 1.41	11.08 ± 1.40	10.37 ± 1.48
Femoral AP/ML ratio	1.05 ± 0.08	0.81 ± 0.05	0.97 ± 0.08
Tibial AP/ML ratio	0.67 ± 0.02	0.71 ± 0.01	0.66 ± 0.02
Demographics			
Submitting province (top)	ON (48.4%)	ON (40.6%)	ON (62.6%)
Diagnosis (% OA)	99.3%	98.8%	99.0%
Age at surgery (years)	67.11 ± 8.09	68.82 ± 8.35	69.77 ± 8.44
Fiscal year	2021.44 ± 1.42	2021.24 ± 1.47	2020.71 ± 1.48

Table F.21: Question B, male cohort cluster associations.

Variable	**Test**	**p-value**	**Effect size**	**Input to clustering?**
Tibial fixation	χ^2	< 0.001	$V = 0.95$	Yes
Tibial symmetry	χ^2	< 0.001	$V = 0.97$	Yes
Femoral model	χ^2	< 0.001	$V = 0.73$	No
Femoral AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.66$	Yes
Tibial AP/ML ratio	ANOVA	< 0.001	$\eta^2 = 0.65$	Yes
Tibial metal material	χ^2	< 0.001	$V = 0.57$	Yes
Insert stability	χ^2	< 0.001	$V = 0.51$	Yes
Insert polyethylene material	χ^2	< 0.001	$V = 0.32$	Yes

Table F.21: Question B, male cohort cluster associations.

Variable	Test	p-value	Effect size	Input to clustering?
Submitting province	χ^2	< 0.001	V = 0.28	No
Patella resurfaced	χ^2	< 0.001	V = 0.26	Yes
Insert thickness	ANOVA	< 0.001	$\eta^2 = 0.069$	Yes
Fiscal year	ANOVA	< 0.001	$\eta^2 = 0.037$	No
Insert mobility	χ^2	< 0.001	V = 0.12	Yes
Age at surgery	ANOVA	< 0.001	$\eta^2 = 0.012$	No
Tibial stem	χ^2	< 0.001	V = 0.08	Yes
Femoral metal material	χ^2	< 0.001	V = 0.07	Yes
Femoral stem	χ^2	< 0.001	V = 0.05	Yes
Diagnosis	χ^2	0.001	V = 0.01	No

Abbreviations: χ^2 = Pearson's chi-squared test of independence; ANOVA = one-way analysis of variance.

Table F.22: Male Question B multinomial logistic regression; reference cluster = Cluster 2, reference year = 2021. Model fit: McFadden R^2 = 0.0251, multiclass AUROC = 0.597.

Cluster (vs. Cluster 2)	Term	OR	95% CI	p-value
	Age at surgery	0.978	0.97-0.98	<0.001
	Fiscal year 2019 (vs. 2021)	0.73	0.68-0.79	<0.001
Cluster 1	Fiscal year 2020 (vs. 2021)	0.92	0.85-0.99	0.033
	Fiscal year 2022 (vs. 2021)	1.06	1.00-1.14	0.069
	Fiscal year 2023 (vs. 2021)	1.16	1.09-1.24	<0.001
	Age at surgery	1.02	1.01-1.02	<0.001
	Fiscal year 2019 (vs. 2021)	1.65	1.56-1.74	<0.001
Cluster 3	Fiscal year 2020 (vs. 2021)	1.31	1.24-1.39	<0.001

Table F.22: Male Question B multinomial logistic regression; reference cluster = Cluster 2, reference year = 2021. Model fit: McFadden R^2 = 0.0251, multiclass AUROC = 0.597.

Cluster (vs. Cluster 2)	**Term**	**OR**	**95% CI**	**p-value**
	Fiscal year 2022 (vs. 2021)	0.80	0.76-0.85	<0.001
	Fiscal year 2023 (vs. 2021)	0.62	0.59-0.65	<0.001