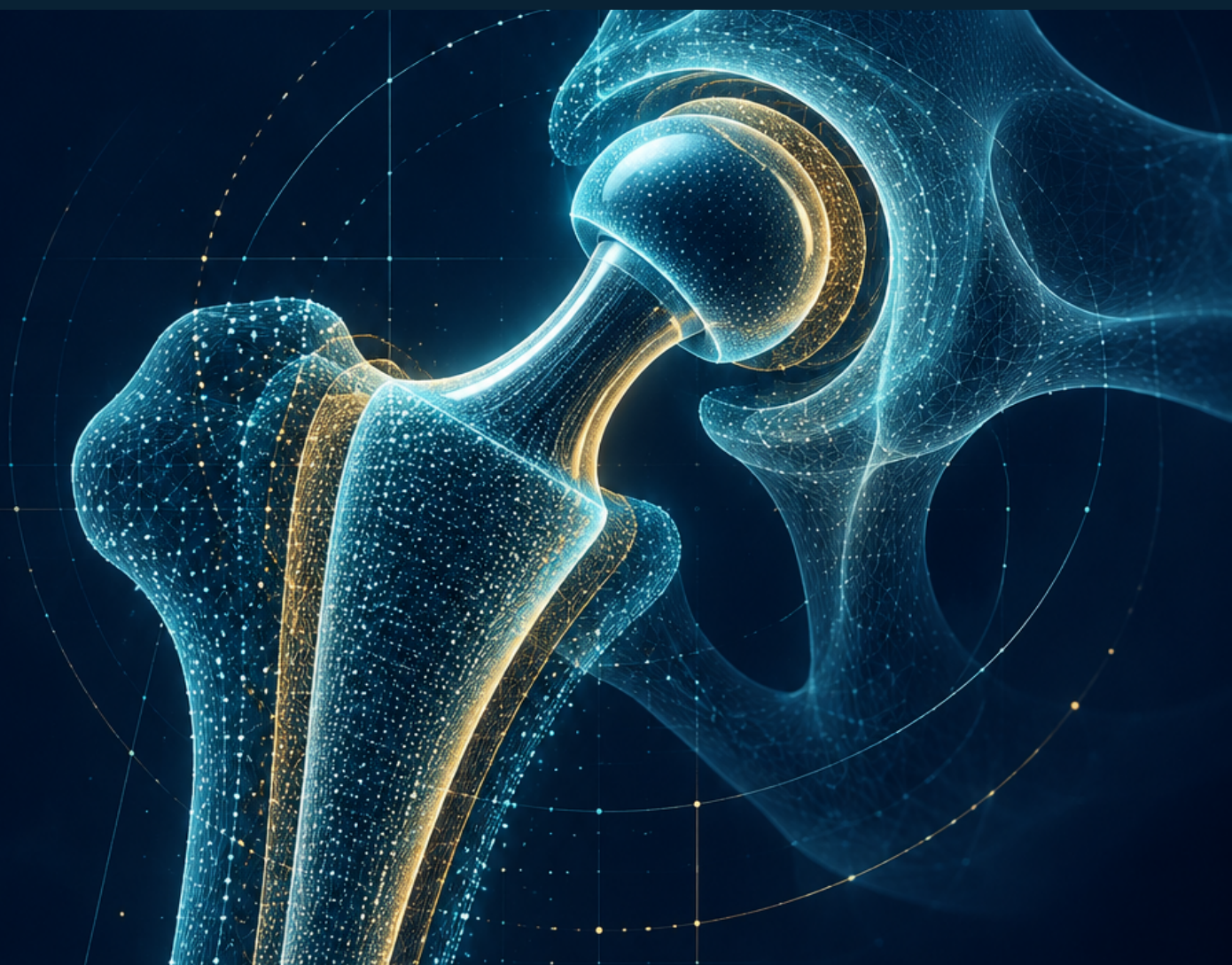


Implant Motion Analysis & CT-based Motion Analysis

Future and Applications



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About this edition

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An illustrated narrative research monograph, developed from the author’s dictated perspective, doctoral thesis, selected Drive-held publications and primary research literature checked for this edition. It is intended for clinicians, researchers and informed readers.

EVIDENCE AND PROPOSALS

Published study findings are cited. Ankle CTMA and frame-removal programmes are author proposals requiring validation; a universal 200 micrometre healing threshold is not established.

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Historical industry relationship: the author’s 2020 femoral symmetry article disclosed a consultancy contract with Sectra [R03]. Current contractual status is not asserted. This monograph does not claim institutional or manufacturer endorsement.

A surgeon's question

I am Mr Peyman Bakhshayesh, MD, PhD, MBA, a Consultant Trauma & Orthopaedic Surgeon and major trauma consultant in Leeds. My interest in motion analysis comes from an everyday surgical problem: an image may suggest that an implant is fixed, or that a fracture has healed, while the patient's symptoms leave us uncertain. Can we measure the mechanical behaviour that a static image cannot reveal?

During my doctoral work at Karolinska Institutet, I used CT-based methods to investigate traumatic pelvic ring injury. The work included a pelvic fracture model, anatomical symmetry and the possibilities of three-dimensional registration. Later, our prospective clinical pelvic study followed displacement after fixation. These studies form the starting point of this book. [R01-R06]

My collaboration with Sectra and its scientific team helped connect clinical questions with computational measurement. I see further opportunities in ankle replacement, fracture healing, the removal of external frames and the assessment of whether a planned reconstruction was achieved. Each opportunity begins with a clinical need; each must earn its place through validation.

This is an illustrated research monograph and an account of future applications. It brings together my perspective, selected published evidence and proposed studies. It is not a systematic review, a device instruction manual or a validated protocol for deciding that an individual fracture is united. Numerical study results are identified as such; proposals are labelled throughout.

The ambition is straightforward: to make motion measurable, interpretation reliable and the result useful to the surgeon and patient. A beautiful three-dimensional image is valuable only when we understand what it measures, how uncertain that measurement is and whether it changes care.

THE CENTRAL QUESTION

What moves, relative to what, under which conditions - and does that movement change the clinical decision?

The collaboration behind the method

My interest in CT-based motion analysis grew from a surgical question: can we measure what changes between two examinations, instead of relying only on what appears to have changed? During my doctoral work at Karolinska Institutet, this question became part of my research into traumatic pelvic ring injuries.

I acknowledge Anders Enocson, my principal doctoral supervisor, and Henrik Olivecrona and the late Lars Weidenhielm, with whom I published our pelvic model study. Their contributions helped connect the clinical problem with the methods needed to investigate it. I also acknowledge Olof Sandberg and our collaboration involving Sectra, including the published work on femoral symmetry.

This research belongs within a wider scientific history. Lotta Olivecrona, Marilyn E. Noz, Gerald Q. Maguire Jr. and Michael P. Zeleznik contributed to publications that developed and tested CT volume registration and orthopaedic measurement. Per Svedmark and colleagues extended these approaches to cervical and lumbar spinal motion. Their published work provides a foundation for the applications discussed in this book.

The subsequent clinical pelvic study, undertaken with Natalie Lundin, Henrik Olivecrona, Lena Gordon Murkes and Anders Enocson, brought these methods into prospective follow-up after surgical fixation. It demonstrated feasibility while leaving important questions about clinical interpretation unanswered.

I recognise these contributions because progress depends on clinicians, radiologists, computational scientists and industry working together. My ambition is to carry that collaboration forward: to test new applications carefully, define their limitations honestly, and make measurements useful for the individual patient facing uncertainty about an implant, a fracture or recovery.

My thesis also acknowledges Karl-Åke Jansson as a co-supervisor. The following register is deliberately publication-based: it distinguishes direct coauthors from scientists whose foundational work belongs to the wider history. It does not assign sole invention to one person, institution or company. [R01]

For transparency, the 2020 femoral symmetry publication disclosed my consultancy contract with Sectra. That is a historical disclosure; this book does not establish a current contractual arrangement or claim endorsement by Sectra, Karolinska Institutet, KTH, the NHS or the University of Leeds. [R03]

Direct collaborators

This publication-based appendix highlights selected contributors and research relevant to CT-based motion analysis. It is not an exhaustive bibliography or a complete account of the field. Direct collaboration with the author is identified where supported by published records; inclusion in the wider scientific history does not imply that every contributor coauthored or supervised the author's research. Institutional roles reflect the cited sources and publications.

Researcher	Contribution and selected publications
Olof Sandberg	Sectra researcher, Linköping, Sweden. Direct coauthor of Bakhshayesh's femoral symmetry study, contributing statistical analysis and manuscript work. His wider publications address hip implant migration, inducible displacement CT and measurement standards. See R03, R16, R17, R18, R19.
Henrik Olivecrona	Orthopaedic researcher, Karolinska Institutet. Direct coauthor in pelvic motion studies. His longstanding work connects CT registration with measurement of implant position, migration and inducible motion, spanning laboratory validation and clinical use. See R02, R06, R09, R10, R14, R18.
Lars Weidenhielm	Karolinska Institutet orthopaedic researcher; remembered CT-RSA pioneer. Direct coauthor and contributor to study design in the 2019 pelvic model study. His publications also address acetabular migration, spinal motion and long-term prosthetic liner wear. See R02, R08, R09, R12, R15.
Anders Enocson	Karolinska Institutet orthopaedic researcher; principal supervisor of Bakhshayesh's PhD. Supported Bakhshayesh's doctoral research and coauthored pelvic motion, anatomical symmetry and lower-limb rotational assessment studies, linking method development to trauma research. See R01, R02, R03, R04, R05, R06.

The wider scientific network

The names below are verified through research publications and institutional records. Marilyn E. Noz’s documented affiliation is New York University; Gerald Q. Maguire Jr.’s institution is KTH Royal Institute of Technology. Their computational contributions should not be reduced to an unverified description of a mathematical algorithm or personal relationship.

Per Svedmark’s publications concern spinal motion; Lotta Olivecrona’s early papers concern acetabular migration. This is a selected map of relevant contributions, not a complete lifetime publication list. [R07-R15, R34]

Researcher	Contribution and selected publications
Per Svedmark	Spinal surgeon and researcher, Karolinska Institutet / Stockholm Spine Center. Published CT-based investigations of cervical disc replacement and lumbar segmental and facet-joint motion. These studies form part of the wider scientific foundation for spinal applications. See R10, R11, R12, R13.
Lotta Olivecrona	Radiology researcher, Karolinska Hospital, Stockholm. First author of early clinical and model studies using CT volume merging to assess acetabular component migration, and a coauthor of subsequent provocation-based loosening work. See R07, R08, R09.
Marilyn E. Noz	Research Professor and Professor Emerita of Radiology, New York University. Contributed to the image-registration and multimodality imaging research underlying orthopaedic CT motion studies; coauthored foundational hip, spine, validation and implant-wear publications. See R07, R08, R10, R12, R14, R15.
Gerald Q. “Chip” Maguire Jr.	Computer scientist; Professor Emeritus, KTH Royal Institute of Technology. Contributed computational and medical-imaging research across the collaboration, with publications on CT volume registration, spinal motion, low-dose validation and implant wear. See R07, R08, R10, R12, R14, R15.
Michael P. Zeleznik	Computing researcher, University of Utah. Recurring coauthor in the computational imaging network, including early CT volume-merging studies and later hip and spinal motion validation. See R07, R08, R09, R10, R12, R14.

From volume merging to clinical questions

The history is cumulative. Early work established that CT volumes could be registered to measure implant position. Experimental studies then examined error; clinical investigations asked whether the resulting measurements could help assess migration or suspected loosening. Trauma applications brought a different problem: fragments can change position during reduction, loading and healing.

The terms have evolved. In this book, CT-based motion analysis is the broad methodological family. CTMA denotes the motion-analysis approaches described in the cited studies and the Sectra product. CT-RSA is the terminology used in contemporary radiostereometric measurement guidance. IMA is Sectra’s Implant Movement Analysis service for clinical questions involving provocation. These related terms are not a guarantee of identical software, protocol or output. [R19, R20, R32, R33]

Period	Selected development
2002-2008	Acetabular CT volume merging, model validation and preliminary cup-loosening work. [R07-R09]
2011-2016	Cervical/lumbar motion studies and experimental low-dose hip comparison with RSA. [R10-R14]
2019-2021	Our pelvic model and symmetry studies; clinical hip precision studies. [R02-R05, R16, R21]
2022-2024	Provocative hip diagnostic study, shoulder and pelvic feasibility, updated RSA/CT-RSA standards. [R06, R18, R19, R22]
2025-2026	Further knee method/dose studies, wrist pilot work and trochanteric fracture agreement research. [R23-R25, R29]

The measurement is relative motion

CT reconstructs a three-dimensional volume from X-ray attenuation measurements. Bone and metal can provide high-contrast structures for registration, but the scan is not simply a shadow of an object. Reconstruction, resolution, noise and metal artefact all affect the information available for matching.

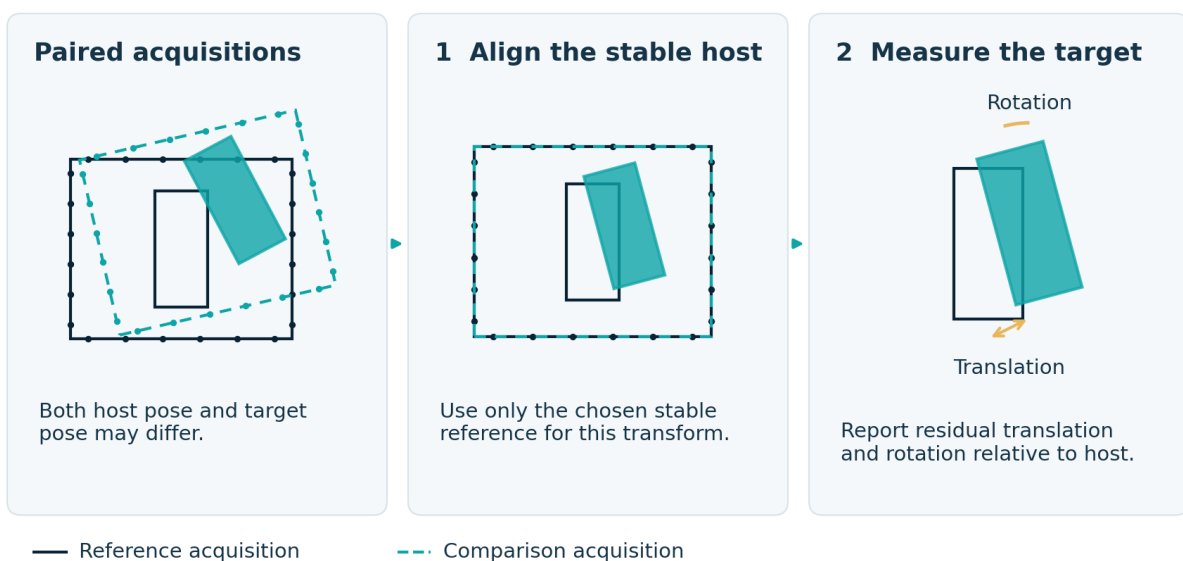
First identify a reference body expected to behave rigidly: for example, the host tibia around an ankle component. Align that body between two acquisitions. This removes differences caused by the patient's overall position in the scanner. Then register the implant or fracture fragment independently and calculate its residual movement relative to the reference body.

A repeatable anatomical region, appropriate exclusion of changing tissue and visual quality control are essential. A reference containing both mobile fragments can absorb some of the motion being investigated. Registering an entire reconstruction as one object can similarly conceal the error of an individual fragment.

The output describes translations and rotations in a declared coordinate system. A displacement at a particular point is calculated from the complete transformation. The clinician must know whether the number refers to a centroid, a point near the implant tip, a surface extremum or a different defined metric. [R19, R20]

Registration separates host and target motion

A conceptual two-dimensional view of a three-dimensional rigid-body analysis.



Schematic only. Registration accuracy and reference stability must be evaluated.

Original schematic. Align the stable reference before measuring residual motion of the target. Shapes and movement are illustrative, not patient data.

Centroid, surface and segmentation

“Centre of mass” is often used informally in clinical discussion. A segmented volume or point cloud usually supplies a geometric centroid unless a justified physical density weighting is applied. A geometric centre and a physical centre of mass are not automatically the same quantity.

Points selected inside an object may represent only a subset of its volume. A surface model may sit inside or outside the apparent boundary depending on thresholds, partial-volume effects, mesh construction and artefact. There is no universal rule that an internal method always underestimates the true object while a surface method always overestimates it.

For motion analysis the central requirement is a consistent, identifiable representation across acquisitions, with its effect on the transformation tested. A smaller clean region may register more reliably than a larger region corrupted by metal artefact. Conversely, too little distinctive geometry can make a registration unstable.

Choose regions before looking at the clinical outcome where possible. Retain screenshots of the masks and the registered overlays. Repeating the analysis with a reasonable alternative region is a useful sensitivity check when a decision rests on a very small measured displacement.

Segmentation defines the measured object

Boundary selection is part of the measurement process, not a guarantee about error direction.

Illustrative nested masks



Uniform scaling is used only to show the idea.

- **Expanded boundary**
- **Nominal boundary**
- - - **Contracted boundary**

In this nested illustration:

The enclosed volume changes with the selected boundary.

Real boundary errors need not be uniform or symmetric.

Centroid bias and registration bias depend on the actual boundary error and analysis method.

Original schematic. Segmented boundaries depend on the method and image quality; the direction of error cannot be inferred from the word “surface” alone.

Why the centre alone is insufficient

A rigid body can translate in three directions and rotate about three axes. For a point p , its transformed position is $p' = Rp + t$. Its displacement is therefore $(R - I)p + t$. R represents rotation and t translation in the chosen frame.

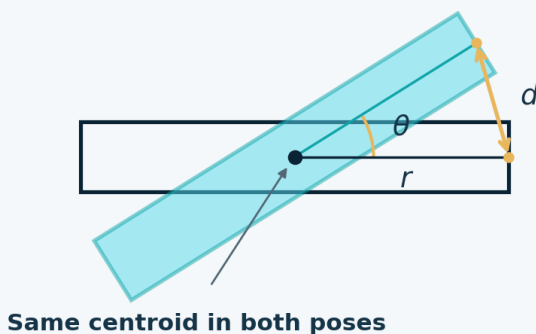
Consider a component rotating around its centre. The centroid can remain stationary while an edge moves. For a pure rotation through angle θ , a point at perpendicular distance r from the rotation axis moves by $d = 2r \sin(\theta/2)$. A zero centroid translation therefore does not prove stability.

The origin and reporting point matter: a rotation produces different translational displacements at different points on the same implant. Report the location explicitly, preserve the coordinate convention across follow-up and compare like with like. Maximum total point motion is also dependent on the points or surface represented; it is not interchangeable with centroid translation.

A clinically useful report shows all relevant translations and rotations, a small set of prespecified anatomical points and the uncertainty associated with those measures. A single attractive colour map should support, rather than replace, these definitions.

A stationary centroid does not imply zero motion

Rigid-body rotation can move the edge while leaving the geometric centroid unchanged.



At a point a distance r
from the rotation axis:

$$d = 2r \sin(\theta/2)$$

d = chord displacement

r = distance from
rotation axis

θ = angle of rotation

Pure rotation; no translation.

Geometric centroid and centre of mass coincide only under suitable density assumptions.

Original mathematical illustration. Rotation can leave the centroid unchanged while producing displacement at the periphery. No clinical threshold is implied.

Precision is not diagnostic accuracy

Accuracy describes closeness to a known true movement. Precision describes repeatability. A method may be highly repeatable yet biased, or unbiased on average but too noisy for an individual decision. Both require testing over clinically relevant ranges.

A zero-motion double examination, including removal and repositioning, tests the combined acquisition-and-analysis process when no biological change is expected. Re-reading the same scan tests only part of that process. Phantom or cadaver experiments with known movement can investigate accuracy, but their conditions do not reproduce every clinical difficulty.

Do not confuse a registration residual with the precision of implant motion. A good fit within one selected region does not establish that the entire object has been identified correctly. Inspect the segmentation, overlap, artefact, geometry and analysis failures.

The 2024 RSA/CT-RSA guideline supports standardised study design and reporting. It is a framework for measurement quality, not a blanket clinical endorsement for every implant or a universal definition of fracture healing. [R19]

Question	Evidence required
Can the method measure movement?	Known-motion accuracy and zero-motion repeatability.
Can it distinguish loose from fixed?	A diagnostic study with an independent reference assessment.
Does it improve care?	Management and patient-outcome studies, including harms and cost.
Can a threshold be transferred?	Validation in the relevant anatomy, implant, protocol and patient population.

REPORTING RULE

A number below the detection capability means that movement was not resolved under the tested conditions. It does not prove that movement is absent.

Two examinations, two different questions

Longitudinal analysis compares scans separated by time. It can describe migration, settling, loss of reduction or change after surgery. The interval and baseline are part of the measurement. Movement between an immediate postoperative scan and one year later is not the same quantity as movement under a load applied today.

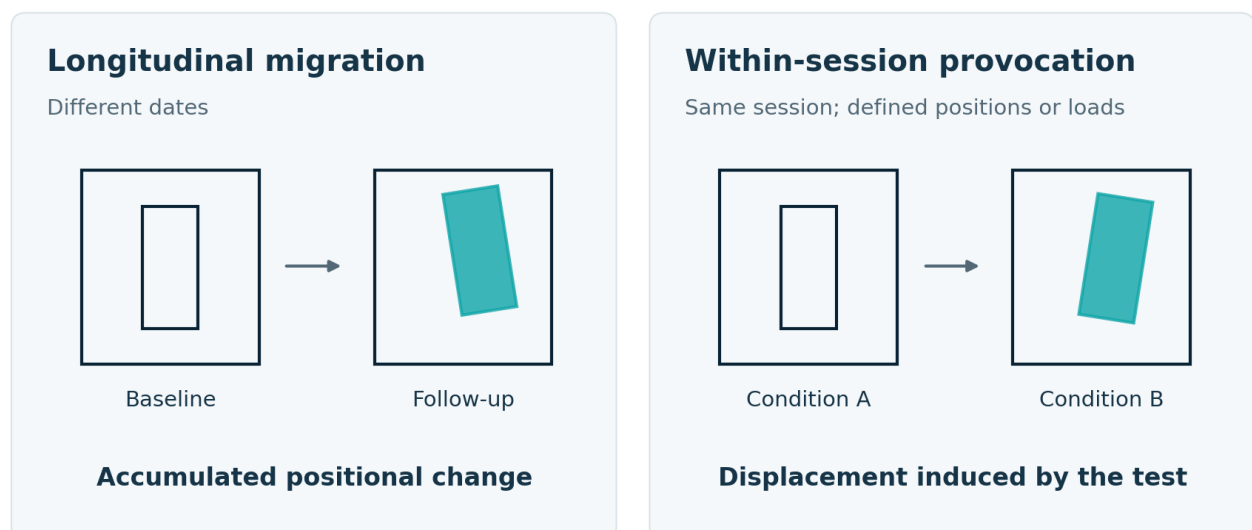
Provocation analysis compares positions or loading states, commonly within one session. It asks whether the target changes position relative to its host when the mechanical environment changes. The achieved posture, load direction and patient tolerance must be recorded; the name of a manoeuvre alone does not specify its mechanical effect.

Neither approach automatically measures stiffness. Within a defined regime, directional stiffness requires a force-displacement or moment-angle relationship. Without measured loading, the result is displacement under the described test conditions. Pain can limit both the range achieved and the reliability of the acquisition.

The two approaches can complement each other. A longitudinally stable component may still show inducible movement. A component that migrated early may subsequently become stable. Their interpretation must remain anchored to the relevant implant and clinical course. [R18, R20, R26]

Two different questions: migration and inducible motion

Both comparisons require a defined reference frame, but they interrogate different changes.



Conceptual paired images. No patient data, numerical scales or diagnostic cut-offs are shown.

Original schematic. Longitudinal migration and within-session inducible motion answer distinct questions. The depicted changes are conceptual.

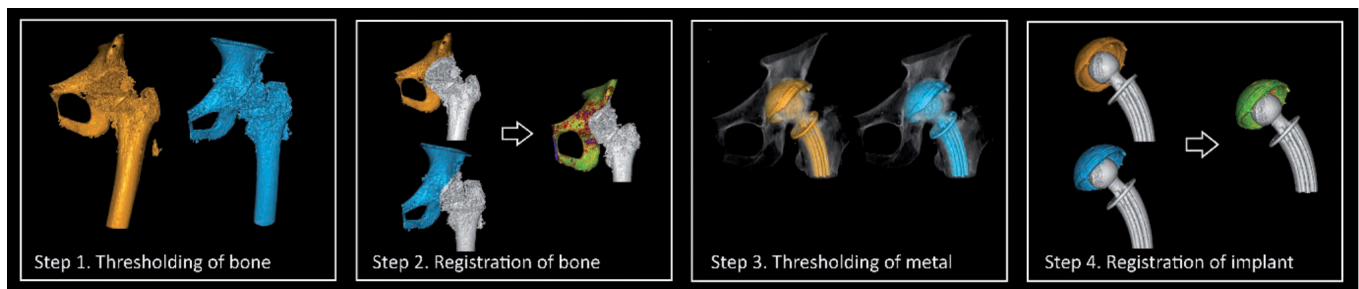
Hip replacement: the strongest starting point

Hip arthroplasty provides an important foundation for CT-based motion analysis. Early volume-merging work and the 2008 preliminary clinical study helped establish the principle of evaluating acetabular fixation with CT. Later studies addressed reduced-dose acquisition and reproducibility. [R07-R09, R14]

Brodén and colleagues studied 24 hip cups using double examinations in 2020. With bone-surface registration, reported translational precision ranged from 0.07 to 0.31 mm and rotational precision from 0.20° to 0.39°. Effective doses ranged from 0.2 to 2.3 mSv. These figures describe the studied settings; they are not guaranteed performance for every scanner or body region. A further 2021 study compared CTMA with RSA. [R16, R21]

For suspected loosening, Sandberg and colleagues' 2022 retrospective study had 57 evaluable patients from 72 recruited. Inducible-displacement CT had reported sensitivity of 77% and specificity of 100%, compared with 59% and 85% for radiographs. The cohort was selected, 15 patients were not evaluable and the reference assessment included surgery or follow-up. These limitations matter when discussing accuracy. [R18]

The implication is encouraging but specific: provocative CT may contribute useful mechanical information in selected painful hip replacements. Precision in migration research and diagnostic performance in suspected loosening are related achievements, not identical outcomes.



Clinical CT registration illustration from Brodén et al. 2020 [R16]. See the figure credits for panel identification and licence.

Knee, spine and upper limb

Knee research includes CT-RSA migration measurement and provocative loosening assessment. A 2025 tibial-component comparison found similar precision to RSA but lower CTMA migration values at one year. This warns against treating different methods as numerically interchangeable. A 2026 study of knee acquisition reported maintained precision with a very low-dose protocol in its particular setting. [R23, R24]

Per Svedmark and colleagues studied cervical disc replacements and lumbar segmental or facet motion. These papers show how three-dimensional registration can describe spinal kinematics. They should not be cited as if every form of spinal implant loosening or pseudarthrosis had the same validated diagnostic threshold. [R10-R13]

Shoulder and wrist applications already appear in the literature. A 2022 clinical feasibility study evaluated cemented glenoid components in seven patients with nine shoulder replacements. A wrist pilot was published online in 2025 and in a 2026 journal issue. Thus, expansion beyond hip and knee is already under way; the task is to strengthen evidence for each specific clinical question. [R22, R29]

An elbow, shoulder, wrist or ankle has different geometry, artefact and expected motion. The size and texture of the reference bone may be decisive. A successful hip registration cannot simply be transplanted without validation.

Application	What the evidence supports
Knee	Migration measurement and growing diagnostic/dose research; study-specific interpretation.
Spine	Three-dimensional kinematic assessment; distinguish intended disc motion from pathological movement.
Shoulder / wrist	Published feasibility or pilot studies; outcome-linked validation remains important.
Ankle replacement	A focused CTMA diagnostic research opportunity in this book, supported by adjacent RSA/foot-method evidence.

The evidence is still expanding

Recent publications show that CT motion research is moving beyond an early hip-focused literature. They also illustrate why findings must remain attached to a specific method and population.

The wrist pilot included three painful total wrist replacements. Displacement was detected in two carpal components, while the radial components appeared stable. This is an informative pilot, not a robust estimate of diagnostic accuracy. [R29]

A prospective knee diagnostic study analysed 34 symptomatic and 38 asymptomatic knees. It reported 91% sensitivity and 72% specificity in the relevant diagnostic assessment. The method used AtMoves, not Sectra; results should not be presented as validation of an interchangeable branded service. [R39]

A September 2026 study investigated 12 painful distal femoral megaprosthetic reconstructions. Ten exceeded the preset movement values. The authors still called for further work to determine reliable cutoffs. The association between pain location and measured motion is a research observation, not proof that pain plus motion invariably establishes loosening. [R38]

Taken together, these studies support a growing field with several implementations. Future work should make the loading procedure, software, coordinate definitions, reference standard and analysis failures transparent. Pooling unlike techniques under one reassuring label would obscure the very distinctions clinicians need.

AN EVOLVING FIELD

Small clinical series identify promising applications. Independent validation is what makes their findings transferable.

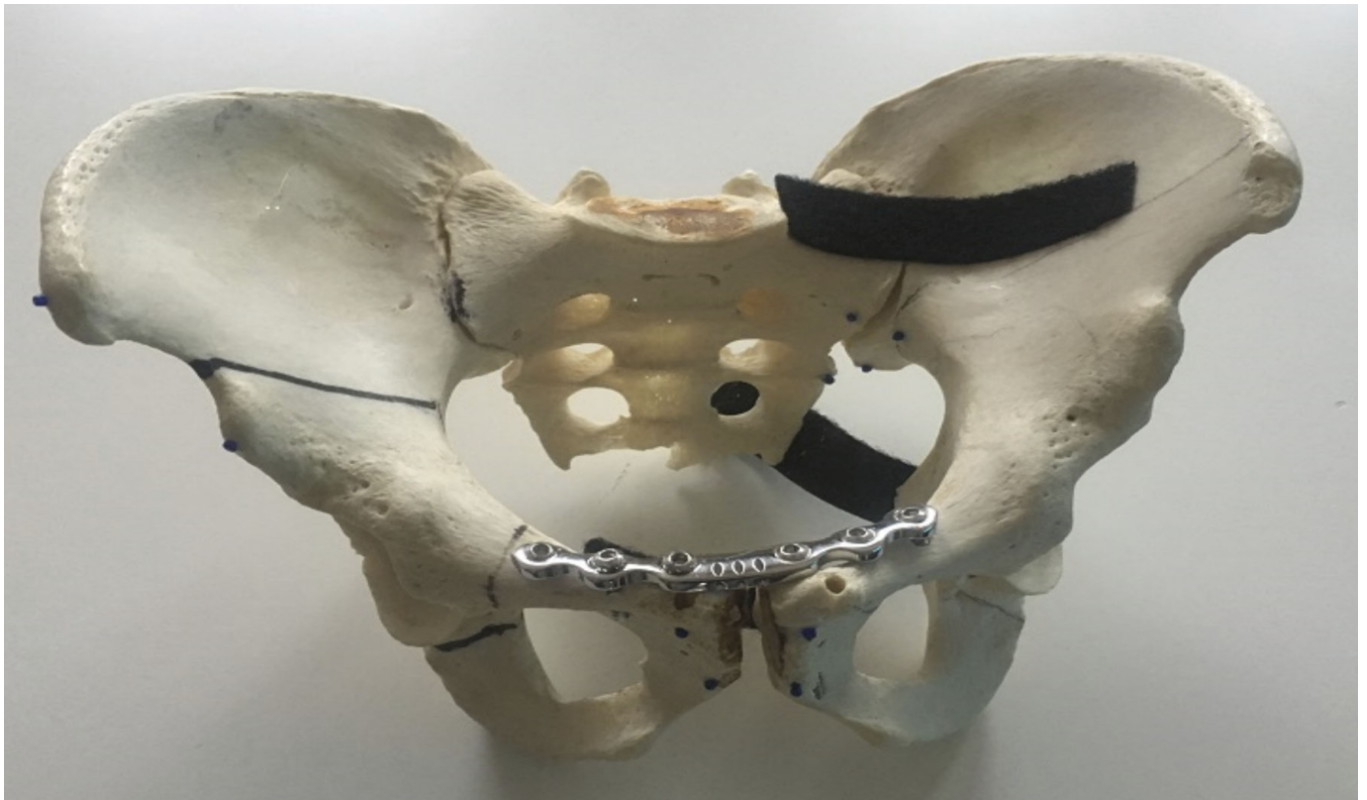
Our pelvic fracture model

Our 2019 paper investigated a new CT-based method for postoperative motion analysis of pelvic fractures. It used a denuded human pelvis with simulated displacement and compared bone-surface and tantalum-marker approaches across seven scan pairs. This was a technical model study, not a series of patients with proven union or nonunion. [R02]

The study demonstrated that translation and rotation could be quantified in a complex pelvic structure. Its published repeatability intervals and inter-method comparisons must be described by the analysis they refer to. In particular, a small inter-method difference is not itself a clinical healing threshold.

The experimental value lay in separating a known mechanical problem from the biological complexity of healing. It allowed the team to ask whether registration could follow the relevant fragments and provide repeatable measurements. It did not determine how much motion a living patient could safely tolerate.

For new applications I would retain that sequence: first test what the system measures under controlled conditions, then investigate clinical feasibility, and only then determine whether it can predict a meaningful outcome.



Pelvic fracture model from the author's doctoral research and published study [R01, R02]. This is a laboratory specimen, not an individual clinical case.

Pelvic follow-up in patients

In the prospective study by Lundin, Olivecrona, Bakhshayesh, Gordon Murkes and Enocson, ten patients underwent CT at baseline and 6, 12 and 52 weeks after pelvic fixation. At one year, median global translation was 6.0 mm and median global rotation 2.6°. Movement was greatest in the first six weeks. [R06]

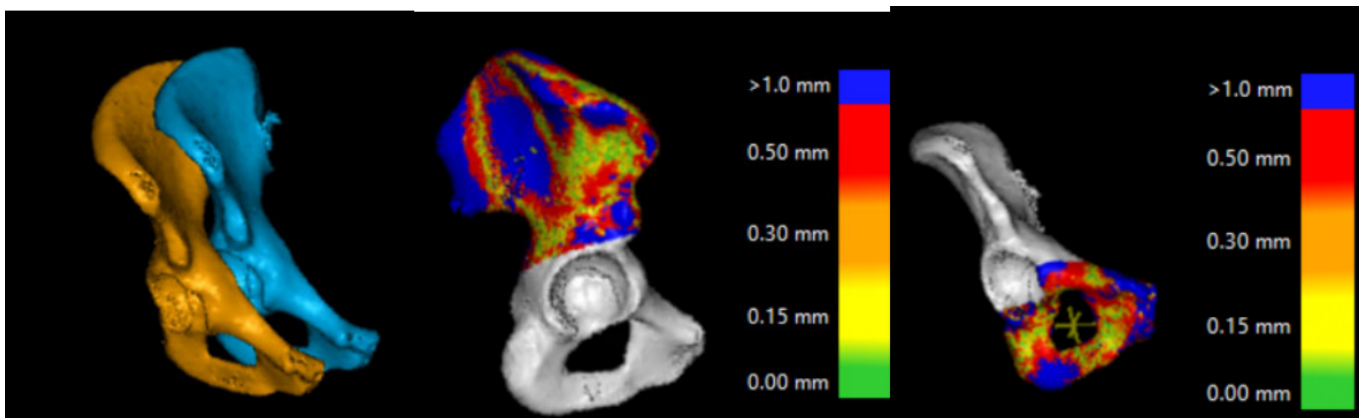
The low-dose follow-up examinations had median effective doses of approximately 0.4-0.5 mSv; the initial postoperative scan used a standard protocol. The study established clinical feasibility and described a course of displacement. It did not establish a cutoff proving union. The authors explicitly identified that as a question for larger studies. [R06]

My interpretation is that this approach adds a dimension to follow-up: the reconstruction can be measured as it changes. Its value may be greatest where conventional views are difficult to reproduce, overlapping pelvic structures obscure detail or a ligamentous injury makes callus-based reasoning incomplete.

The reference region deserves special attention. An intact hemipelvis can provide a useful anchor in selected injuries; a bilateral injury may require another suitable reference. Each case needs a defensible mechanical model. Global displacement, local articular incongruity and symptoms should be reported separately.

A FEASIBILITY RESULT

The study supports measuring postoperative pelvic movement. It does not validate CTMA as a stand-alone test of healing.



Example of three-dimensional pelvic registration from the author's research archive [R01]. This image explains the method; the 2023 clinical results are reported separately in the text.

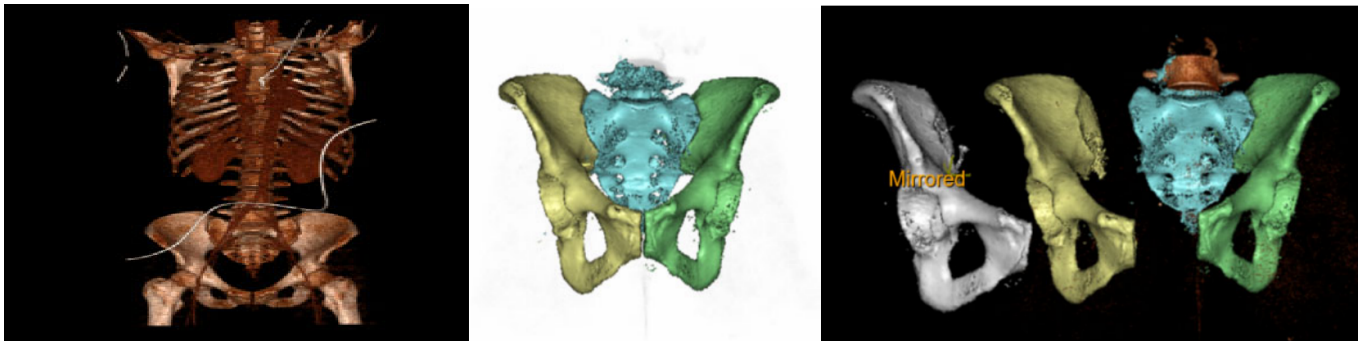
Symmetry as a reconstruction aid

A mirrored contralateral bone offers an intuitive reference for reconstruction. Our work investigated femoral symmetry, hemipelvic symmetry and rotational assessment of the lower limb using CT-based approaches. These studies connect motion analysis with three-dimensional anatomy and deformity assessment. [R03-R05]

The contralateral side is a reference, not an unquestionable template. Natural asymmetry, previous injury, developmental variation, arthritis or deformity can change what a mirror image means. A plan should record those assumptions instead of disguising them inside an apparently exact surface match.

This distinction becomes useful when planning correction of length, rotation or translation. A registration can quantify the relationship between two models, but the surgeon still determines which anatomical relationship is desirable. The intended reconstruction must also respect the joint surface, soft-tissue envelope, fixation strategy and attainable exposure.

When the plan is preserved, it becomes possible to evaluate its execution. The next question is no longer simply whether a postoperative image looks satisfactory, but how far each reconstructed fragment lies from the agreed target.



Mirroring and reconstruction workflow from the author's doctoral material [R01, R04]. Contralateral anatomy supplies a reference whose assumptions must be examined.

Planned versus achieved reconstruction

My proposal is to preserve the preoperative virtual reduction, acquire an appropriately justified postoperative CT and compare the achieved reconstruction with the plan. Sectra’s three-dimensional planning environment is one possible platform; the scientific requirement is an exportable and reproducible coordinate system, not a particular brand. [R40]

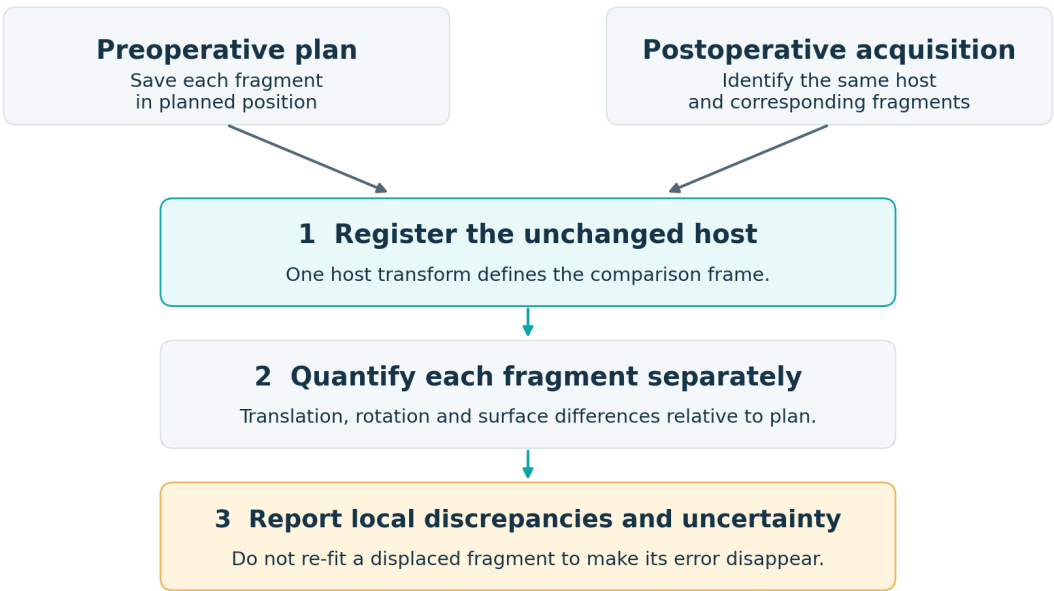
Align the postoperative scan to unchanged reference anatomy. Then compare each fragment with its planned pose. Report translation and rotation, articular step and gap, length and overall alignment as distinct outcomes. A global best fit across all fragments may make a poor reduction appear closer to the target by distributing the error.

Recent work strengthens the rationale. Åberg and colleagues’ 2026 trochanteric fracture agreement study enrolled 15 patients, with complete imaging in 12, and used CTMA and a mirrored contralateral reference to quantify reconstruction and later change. It supports measurement feasibility; it does not prove that every virtual plan improves patient outcomes. [R25]

A clinically useful study would test both questions: can planned-versus-achieved error be measured reliably, and does a smaller error predict better function, fewer complications or less reoperation? A plan can be reproduced precisely and still be clinically inappropriate.

Assess reconstruction in a fixed reference frame

Keep the reference transformation separate from the errors of individual fragments.



Conceptual quality-assessment workflow; image quality and the suitability of the host must be checked.

Original proposed workflow. Compare individual fragments after aligning unchanged reference anatomy; preserve the preoperative target for audit.

Fracture healing is more than a number

Healing restores the ability of the injured structure to carry load. Motion is therefore relevant, but its meaning depends on the applied force, direction, fracture gap, fixation, stage of healing and the tissue being assessed. A measurement without those conditions is incomplete.

The suggested value of 200 micrometres equals 0.2 mm. It must not be used as a universal CTMA definition of union. Published work uses similar numerical values for other purposes, including registration colour intervals. The pelvic clinical study called for future work to establish a healing cutoff. [R06, R28]

A simple mathematical example explains the difficulty. A displacement of 0.2 mm across a 1 mm gap corresponds to 20% nominal axial strain; the same displacement across a 10 mm gap corresponds to 2%. These are arithmetic illustrations, not tissue-tolerance limits or clinical union criteria. Rotation and shear add further complexity.

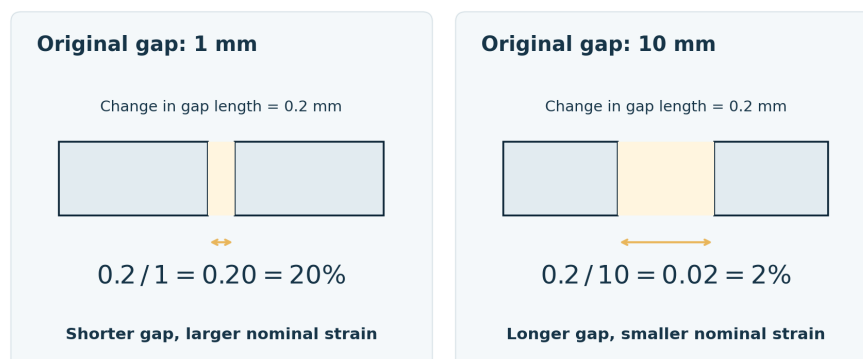
Persistent reproducible motion with pain can raise concern about inadequate stability, but it does not by itself establish delayed union or nonunion. Assess the time course, serial morphology, clinical progress, infection, biological environment and construct. Conversely, low observed motion in a stiff construct can coexist with incomplete biological healing.

THE CLAIM TO TEST

Can a reproducible mechanical measurement improve prediction of healing or failure beyond current clinical and radiological assessment?

The same displacement can imply different gap strain

A mathematical example: strain = change in gap length / original gap length.



Mathematical illustration, not healing thresholds. Schematic gaps are not drawn to scale.

A complex fracture has spatially varying motion; a single gap-strain ratio is a simplification.

Original mathematical example: nominal strain = change in gap / initial gap. The percentages are not validated healing thresholds.

Before removing an external frame

A frame may be removed after clinical and imaging assessment suggests healing, yet the bone can subsequently deform or fracture again. The challenge is to estimate whether the limb can carry its expected load after support is withdrawn. A CT appearance alone does not directly measure that capacity.

CT motion analysis could be investigated as an additional mechanical assessment. Begin with a defined fracture site and construct type rather than pooling traumatic fractures, infected nonunions and distraction regenerate. Establish repeatability before testing predictive thresholds.

The frame is a major confounder. If it prevents the fragments from moving, a low-motion result may reflect the frame rather than the healed bone. The study must record construct stiffness, dynamisation state, loading and load sharing. Any alteration of frame mechanics would require a supervised, approved protocol; this book does not propose unsupervised stress testing or removal.

Historical tibial fracture work on directly measured stiffness supports the importance of multidirectional mechanical assessment. It does not validate CTMA or a 0.2 mm threshold for frame removal. A CTMA programme would need prospective outcome validation against refracture, deformity and unplanned re-fixation. [R27]

Phase	Question and endpoint
Technical	Can fracture-to-fracture motion be measured despite frame metal and limited reference surfaces?
Feasibility	Can a standardised, tolerable load be delivered and documented?
Prediction	Does the measurement improve prediction of refracture or deformity?
Clinical utility	Does using the result improve safe removal timing and patient function?

MEASURE THE RIGHT SYSTEM

Document whether the frame or the healing bone is carrying the load. A low-motion reading inside a stiff frame may be falsely reassuring.

Ankle replacement: the clinical need

For my foot-and-ankle practice, a painful ankle replacement is a particularly important application. The central question is whether pain comes from a loose component, an impinging structure, adjacent-joint disease, infection, a stress injury or another cause. Revision is consequential; uncertainty deserves a careful investigation.

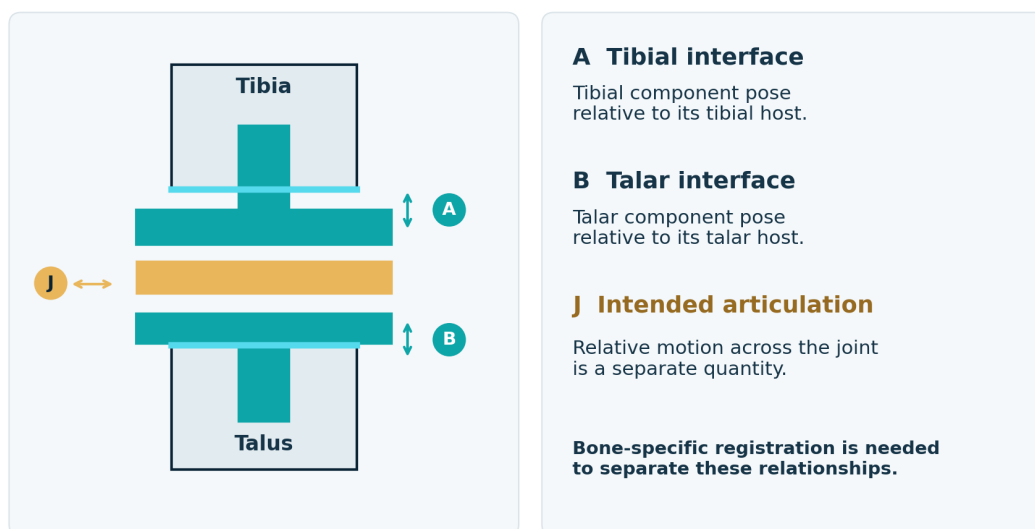
Conventional assessment remains essential. Weight-bearing radiographs show alignment, subsidence and radiolucency. CT can characterise bone loss and component position. Selected MRI or SPECT/CT can answer additional soft-tissue or metabolic questions. Published ankle studies support the use of CT and SPECT/CT in appropriate diagnostic settings, but each modality has limits. [R30, R31, R36]

The attraction of provocative CTMA is direct assessment of component-to-bone movement. A component that moves relative to its host under a reproducible test may provide a more mechanical explanation than a static appearance alone. That possibility must be validated specifically in ankle arthroplasty.

Ankle RSA research and CT-RSA midfoot studies provide useful adjacent evidence. They do not establish that dorsiflexion and plantarflexion CTMA can already diagnose ankle loosening with a validated accuracy or threshold. In this book, the ankle programme is explicitly a proposal. [R26, R35]

Component-to-bone motion is distinct from joint motion

Mechanical analogy for ankle arthroplasty analysis - not an anatomical or device drawing.



Schematic relationships only. No implant geometry, motion threshold or validated ankle protocol is implied.

Original simplified interface schematic. Measure tibial component relative to tibia and talar component relative to talus; intended articulation between components is a different motion.

A staged ankle CTMA programme

The first stage would test phantoms and cadaver constructs with known movements across representative ankle designs. Repeat acquisitions after repositioning would establish zero-motion precision. The analysis should examine small talar reference regions, implant artefact, segmentation choices and whether different observers reach similar results.

A subsequent feasibility cohort could include stable asymptomatic replacements and symptomatic cases. Neutral, plantarflexed and dorsiflexed positions are candidates for investigation, not a requirement to force the ankle into hyperflexion. Compare their reproducibility, tolerance and actual effect on interface loading; axial loading may answer a different question.

Record the achieved angle, load or torque where feasible, positioning aids, pain and incomplete examinations. More range of joint motion does not necessarily produce more useful interface loading. An inability to reach the proposed position is a finding, not a reason to assume that a negative test is conclusive.

For analysis, register the tibia and tibial component separately; then register the talus and talar component separately. The expected articulation between the two prosthetic surfaces must not be labelled loosening. A mobile bearing requires its own visibility and tracking assessment.

Only after technical validation should a prospective diagnostic study derive and externally validate criteria. Revision findings, when surgery is independently indicated, and structured follow-up in non-revised patients can inform a reference assessment. Blinding and verification bias must be addressed.

Stage	Primary deliverable
1. Technical	Accuracy, repeatability, artefact sensitivity and failure rate.
2. Feasibility	Tolerable and reproducible acquisition; specified loading.
3. Diagnostic	Sensitivity/specificity with uncertainty and an independent reference.
4. Utility	Effect on decisions, revision findings, function, dose and cost.

How motion fits into clinical assessment

CTMA adds a mechanical measurement to a clinical assessment. It cannot establish that movement is aseptic, and a mechanically stable implant does not exclude another important source of pain. The diagnostic pathway should begin with the question being asked and use the modality most capable of answering it.

Clinical examination and the temporal pattern of symptoms remain central. Blood tests, aspiration and microbiological assessment may be indicated when infection is suspected. Inflammatory markers alone do not settle that question. Motion findings must be interpreted alongside the appropriate infection pathway, rather than used to bypass it.

For an ankle replacement, the report should distinguish component fixation from adjacent-joint disease, impingement, alignment, fracture and soft-tissue pathology. Different findings may coexist. A negative provocative study is limited by achieved loading, measurement uncertainty and the region actually analysed.

The practical decision is whether the additional information changes management responsibly. A test may be technically impressive yet add little in a case where conventional imaging already establishes the problem. It may be valuable when the remaining uncertainty is specifically mechanical.

Modality / assessment	Principal contribution
Clinical evaluation	Symptoms, function, loading tolerance and alternative explanations.
Radiographs	Alignment, component position and interval structural change.
CT	Bone, osteolysis, fracture morphology and implant relationships.
MRI / SPECT-CT when indicated	Selected soft-tissue or metabolic questions; interpret artefact and nonspecific uptake.
CT motion analysis	Relative movement under defined temporal or loading conditions.
Infection investigations	A separate clinical and microbiological question; movement cannot determine cause.

INTERPRETATION

Concordant symptoms and reproducible motion strengthen a mechanical hypothesis. They do not remove the need to consider other causes.

Low dose requires a validated protocol

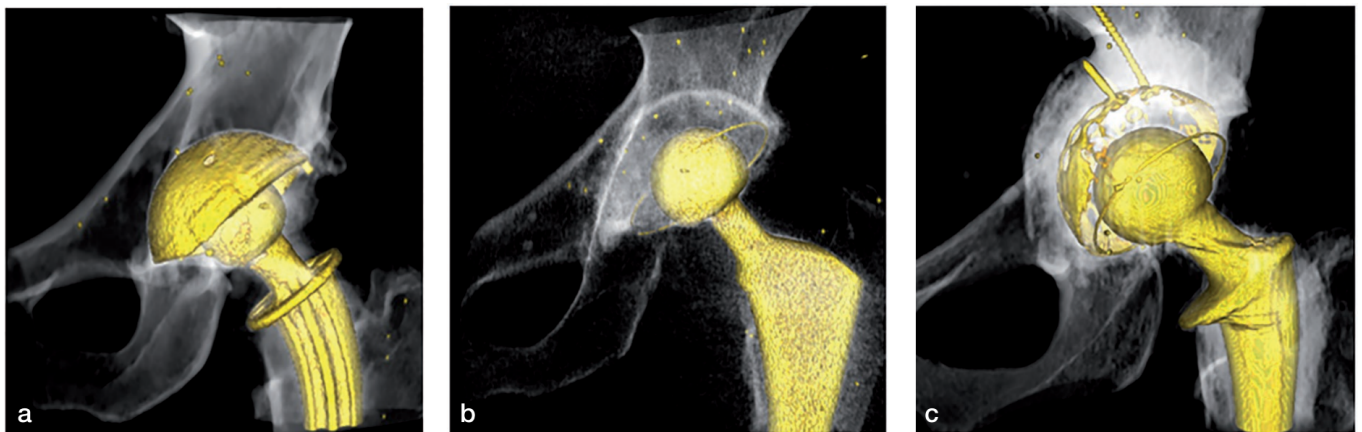
The opportunity is to obtain enough information for reliable registration at the lowest justified radiation exposure. Bone and metal contrast can help, but lower dose also increases noise. The whole acquisition and reconstruction pipeline must be tested with the intended measurement task.

Anatomy, body size, scan length, implant material, scanner, slice geometry and reconstruction affect performance. Follow-up should use a documented, consistent protocol where possible. Metal artefact reduction can be useful, but its effect on boundaries and registration must be examined rather than assumed.

Published dose numbers are examples, not prescriptions: the 2020 hip study reported 0.2-2.3 mSv, the pelvic clinical study approximately 0.4-0.5 mSv for low-dose follow-up scans, and a 2026 knee study evaluated substantially lower region-specific doses. These examinations have different anatomy and purposes. [R16, R06, R24]

Report exposure for the complete examination, including repeated acquisitions and the number of positions. Do not quote a per-scan figure as if it were the total for a provocative series. Repeat scanning needs clinical justification; motion-corrupted or insufficiently loaded acquisitions should be reported transparently.

The author's Drive archive contains Sectra's 2021 acquisition guide. It is a historical source, not a substitute for current local radiology, physics and manufacturer guidance. A current service should define patient preparation, positioning, transfer, quality control, analysis and clinical reporting before accepting referrals. [R37]



CT reconstructions of three acetabular cup constructs studied by Brodén et al. 2020 [R16], Figure 1. Source attribution and licence are listed in the figure credits.

A report that a surgeon can use

A useful result is reproducible, interpretable and explicit about limitations. The following template is an author-proposed structure for discussion with radiology and research teams, not an official Sectra report form.

A conclusion should state the observation before the interpretation: for example, that movement above the established measurement uncertainty was identified at a specified interface under the achieved test conditions. Avoid an unqualified “loose” or “healed” label when the application has not been clinically validated.

Report field	Required content
Question	Migration over time, inducible movement or deviation from a surgical plan.
Acquisition	Dates, scanner/protocol, positions, scan count, dose and image quality.
Mechanical conditions	Achieved posture, load/torque if measured, pain/tolerance and frame state.
Reference and target	Host region, component/fragment, exclusions, software/version and coordinate system.
Results	Translations, rotations and defined reporting points; interval or load comparison.
Uncertainty	Relevant repeatability, registration checks and failed or indeterminate analyses.
Interpretation	Relationship to the clinical question, evidence status and alternative explanations.
Next step	What the result can reasonably support; what remains unresolved.

ILLUSTRATIVE WORDING - NO PATIENT DATA

“The target component demonstrated measurable movement relative to its host bone under the documented conditions. Clinical interpretation requires correlation with symptoms, structural imaging and assessment for other causes.”

Designing the next studies

The next generation of studies should start with the decision they aim to improve. Implant migration research, diagnosis of a painful replacement, fracture-healing prediction and reconstruction audit have different outcomes and require different designs.

Technical studies should predefine regions, coordinate systems, outputs and acceptable analysis failure rates. Use known-motion tests and repositioned double examinations. Include challenging implant designs and metal artefact rather than reporting only ideal examples.

Diagnostic studies should recruit consecutive relevant patients, blind image analysis to the reference assessment and predeclare how indeterminate examinations will be handled. Operative findings are valuable but available only in selected patients; a mixture of surgery and follow-up creates verification limitations that must be described.

Prognostic studies should retain motion as a continuous variable initially. Deriving a convenient cutoff from a small sample risks overfitting. A proposed threshold needs external validation and should be compared with existing clinical and imaging predictors.

A service evaluation should measure more than precision: changes in treatment, unnecessary or delayed revision, refracture, patient-reported function, access, radiation and cost. Sample size should be planned around the primary outcome and its uncertainty, rather than copied from an early pilot.

Research access and industry collaboration can accelerate development. Independent analysis, transparent declarations and publication of failures are equally important. Standardisation will be useful only if it makes studies comparable and measurements trustworthy. [R19, R20]

FOUR SEPARATE TESTS

Technical validity → clinical validity → effect on decisions → benefit for patients. Success at one stage does not automatically establish the next.

Access, applications and the future

Sectra currently describes CTMA for motion measurements over time or between loading conditions, and IMA for assessment using paired CT examinations. Availability, contractual scope, analysis support and charges need confirmation for the relevant service. No unverified price is quoted here. [R32, R33]

The clinical ambition is wider access to a dependable measurement. A practical service requires radiographers who can reproduce the acquisition, radiologists and physicists who can optimise it, analysts who understand registration, and surgeons who can connect the result to a decision. Software alone cannot supply this chain.

In trauma, I see opportunities to follow displacement, assess deformity, evaluate reconstruction and investigate healing. In arthroplasty, I see opportunities to separate intended articulation from loss of fixation. In ankle replacement and external-frame care, the unanswered questions are particularly relevant to my practice.

Automation may reduce the time needed for segmentation, registration and reporting. Its value will depend on recognisable failure modes, reviewable outputs and continued validation. Faster production of an uncertain number is not progress unless the uncertainty is visible.

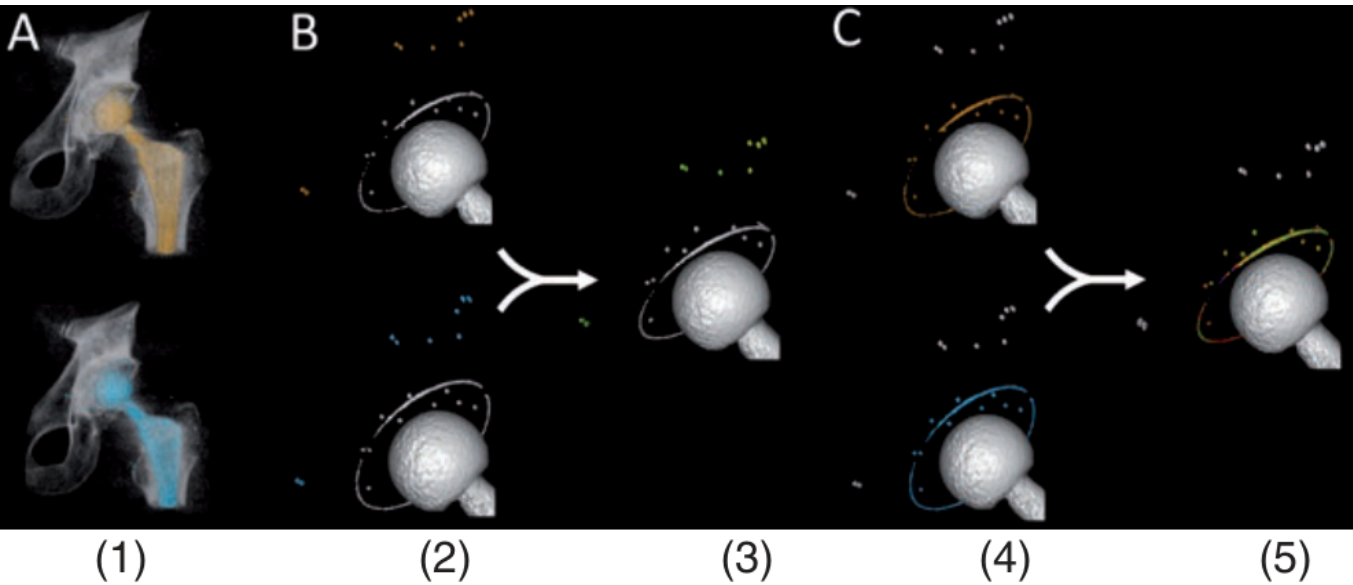
My hope is that CT-based motion analysis becomes a more accessible bridge between structural imaging and mechanical understanding. The aim is not to replace clinical judgement with a decimal place. It is to give judgement better evidence: a clear account of what moved, how it was measured and why it matters to this patient.

FUTURE APPLICATIONS

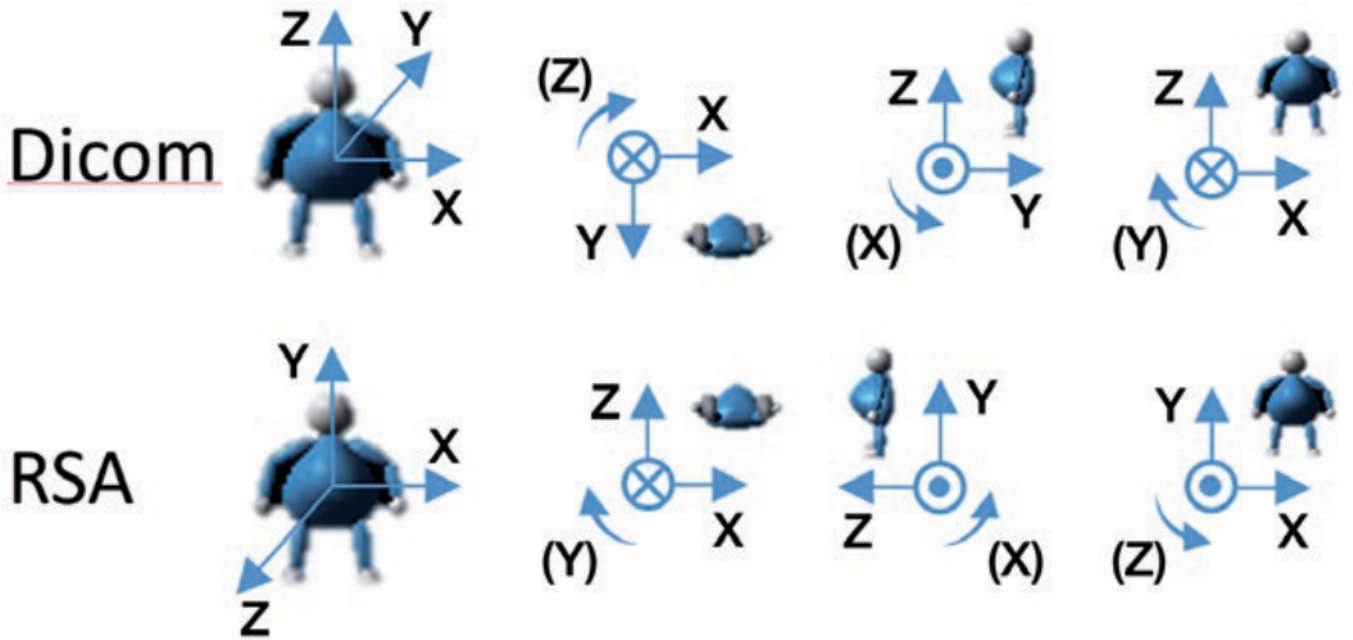
Ankle component fixation • fracture-healing research • external-frame removal studies • reconstruction audit • longitudinal implant surveillance

The CT registration workflow

The following source illustrations show how reference objects and coordinate conventions enter the analysis. They are published research examples, not new patient results from the author’s practice.



Marker-based pelvic registration and cup registration. Brodén et al. 2021, Figure 1 [R21], CC BY 4.0. Original panel labels retained.



DICOM-based CTMA and RSA coordinate conventions. Brodén et al. 2021, Figure 2 [R21], CC BY 4.0. Axes and sign conventions must be reconciled before comparing outputs.

Image sources and permissions

Scientific figures are separated from conceptual illustrations. The images reproduced here were inspected for identifying overlays and matched to their source captions. Unrelated Drive photographs were not used.

Source: Bakhshayesh, doctoral thesis, Karolinska Institutet, 2020, Fig. 5. Extracted image only; no scientific alterations. Author-owned source used at the author's request.

Source: Bakhshayesh, doctoral thesis, Karolinska Institutet, 2020, Fig. 7. Extracted image strip only; no scientific alterations. Author-owned source used at the author's request.

Source: Bakhshayesh, doctoral thesis, Karolinska Institutet, 2020, Fig. 8 (left three panels). Cropped to the first three panels of Figure 8; final user-interface panel omitted. No image content within retained panels altered. Author-owned source used at the author's request.

Brodén et al., Acta Orthopaedica 2020, Fig. 1. CC BY 4.0. doi:10.1080/17453674.2020.1725345. Image extracted from the published figure, with original panel labels retained.

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Brodén et al., Acta Orthopaedica 2021, Fig. 1. CC BY 4.0. doi:10.1080/17453674.2021.1906082. Image extracted with original step numbers retained.

Brodén et al., Acta Orthopaedica 2021, Fig. 2. CC BY 4.0. doi:10.1080/17453674.2021.1906082. Image extracted without scientific alterations.

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Seven new explanatory diagrams were created for this edition: two-step registration; centroid and rotation; segmentation boundaries; longitudinal versus provocative analysis; gap-strain arithmetic; planned versus achieved reconstruction; and ankle component-to-host relationships. They are schematics and contain no measured patient data.

Cover artwork is AI-generated and conceptual. It illustrates the theme of registration; it is not a validated anatomical reconstruction, CT scan or result. Editorial synthesis and original diagrams were prepared with AI assistance from the author's instructions and checked against the cited sources.

Terms used in this book

Term	Meaning in this monograph
CTMA / CT-RSA	CT-based registration approaches used to quantify motion; specify the exact implementation.
IMA	Sectra Implant Movement Analysis; paired CT assessment for clinical mechanical questions.
Registration	Estimation of the spatial transformation aligning corresponding structures.
Centroid	Geometric centre of a defined volume or point set; not necessarily a physical centre of mass.
Migration	Change in position between examinations at different times.
Inducible motion	Change between defined mechanical conditions, commonly within a session.
Precision	Repeatability of a measurement under the stated conditions.
Accuracy	Agreement with a known true value.
Registration residual	Remaining mismatch within the registered data; distinct from overall motion-measurement uncertainty.
Six degrees of freedom	Three translations and three rotations.
MTPM	Maximum total point motion over the defined represented points or surface.
Stiffness	Force/displacement or moment/angle relationship in a specified direction and regime.
Union	Clinical and biological recovery assessed in context; not a universal CTMA displacement threshold.

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