**Supplementary materials**

## Surgical appendix

The procedure was performed through a posterior midline approach with a standard olecranon osteotomy to expose the distal humeral articular and metaphyseal-shaft region. All previous hardware was removed, and soft-tissue adhesions were carefully debrided. A patient-specific cutting guide was positioned on the distal humeral diaphysis and secured with 1.6-mm Kirschner wires, ensuring full seating on the cortical surface (Figure 2B). The osteotomy of the distal diaphysis was then completed with a ≤0.6-mm oscillating saw following the guide trajectory. After removing the K-wires and guide, the resected diaphyseal segment was extracted, and the medullary canal was sequentially reamed to the planned diameter.

The custom-made prosthetic construct (Figure 2E) was then introduced, with the proximal stem cemented in the humeral canal according to manufacturer specifications. Distally, the dual-branch design was aligned to achieve full apposition with the remaining humeral cortex. Screw fixation holes were identified using the guide-generated entry points, and definitive fixation was achieved with cortical screws placed through the distal flanges into native bone (Figure 2F). A compression screw could be added for optional distal interlocking if required.

The olecranon osteotomy was reduced anatomically and fixed with standard tension fixation per surgeon preference (Figure 3). Wound closure was performed in layers after thorough irrigation, and the limb was immobilized in a posterior splint before transfer to recovery.

## Rehabilitation appendix

Resume in table 1

### Immobilization and Support

- **0–10 days:** posterior splint or removable hinged elbow brace at 60–70° flexion for comfort; sling for ambulation.
- **After Day 10:** transition to **hinged brace** unlocked for prescribed ROM; wear outside therapy until Phase III.

### Phase I — Protection & Edema Control (Post-op Day 1 to Week 2)

### Goals

- Pain ≤3/10 at rest; edema control; wound healing.
- Maintain shoulder/hand mobility; protect fixation.

**Interventions**

- Cryotherapy, elevation, hand pumping.
- Shoulder: pendulums, scapular setting, passive/active-assist flexion to 90° (as tolerated), no resisted extension.
- Elbow/forearm (brace-guided): **passive → active-assist ROM** within pain-free arc, typically **flexion to 90–100°**, **extension limited to −30/−40°** (matches baseline extension loss of 36.2°).
- Forearm rotation: **AAROM pronation/supination to ~80–85°** with elbow at 90° flexion.
- Neural mobility: gentle, symptom-free radial/median/ulnar nerve sliders.
- Cardiovascular: walking, stationary bike (arm supported).

**Criteria to Progress**

- Incision healed; pain ≤3/10 with ROM; no neurovascular change; flexion ≥100°, extension deficit ≤30°.

**Phase II — Early Motion & Muscle Activation (Weeks 2–6)**

**Goals**

- Restore functional arc: **flexion 110–120°, extension deficit ≤20°** by Week 6.
- Forearm rotation symmetrical by end of phase.
- Normalize scapulohumeral rhythm; protect alignment (TCI monitoring).

**Interventions**

- **AAROM → AROM** elbow within tolerance; low-load, long-duration **extension hangs** (5–10 min, 3–5×/day) avoiding pain.
- **Active forearm rotation** with elbow at 90°, progress to elbow-at-side neutral.
- **Isometrics (sub-max)**: biceps, brachialis; **avoid resisted triceps** until Week 4–6 if cleared.
- **Scapular strengthening:** serratus, lower trap, rhomboids (closed-chain scapular clocks on table).
- **Posture/kinetic chain:** thoracic mobility, cervical/first rib mechanics.
- Manual therapy: soft-tissue to posterior arm; gentle joint mobilizations (humeroulnar grade I–II).
- Brace: gradually increase extension by 5–10°/session based on tolerance.

**Criteria to Progress**

- Flexion ≥120°, extension deficit ≤20°; pronation/supination ≥85° each; light ADLs without compensation; MEPS ≥80.

**Phase III — Strength & Functional Arc Restoration (Weeks 6–12)**

**Goals**

- Achieve **flexion 130–135°**, **extension deficit ≤10°** by Week 12.
- Forearm rotation equal to the contralateral side.
- MEPS ≥90 ("excellent" range).
- Radiographic signs of progressive union without implant complications.

**Interventions**

- **AROM to end range**; continue low-load extension stretching.
- **Progressive resistance (2–3×/week):**
    - Elbow flexors/extensors: start **1–2 kg** isotonic; progress per tolerance.
    - Forearm pronators/supinators: hammer rotations, elastic bands.
    - Wrist complex: curls, extensions, RD/UD, grip dynamometer work.
- **Closed-chain**: wall push-ups (partial range), weight shifts with elbow flexed 15–45°.
- **Proprioception**: rhythmic stabilization at various elbow angles; perturbation training.
- **Task-specific ADLs**: reach to head/behind-neck hygiene; light household tasks.
- **Conditioning**: upper-body ergometer (short cranks) as tolerated.

**Criteria to Progress**

- Pain ≤2/10 with resisted tasks; flexion ≥130°, extension loss ≤10°; symmetrical rotation; no increase in swelling 24 h post-exercise; stable radiographs at 12 weeks.

**Phase IV — Advanced Strength, Endurance & Return to Work/Sport (Months 3–6)**

**Goals**

- **ROM:** flexion **135–140°**, extension loss **≤5°** (or patient-specific target).
- **Strength:** ≥85–90% of contralateral limb by hand-held dynamometry.
- **Function:** MEPS ≥95; patient-reported outcomes in "excellent" band.

**Interventions**

- **Progressive triceps loading** (skull-crusher variants within pain-free range), compound pushing/pulling (row, cable press) with graded loads.
- Plyometric preparation: rebounder chest passes with light ball (≤1–2 kg), perturbation in terminal ranges.
- **Work-conditioning**: lifting mechanics, carry tasks at chest level → waist level; ergonomics coaching.
- Sport-specific drills (non-contact) as indicated.

**Criteria for Unrestricted Activity (after Month 6)**

- Full/patient-acceptable ROM; strength ≥90–95% vs. contralateral; no pain/effusion after high-demand sessions; radiographic union confirmed.

**Custom-made implant planning appendix**

**Image Acquisition Technique Used in the Preoperative Phase (RADIOLOGICAL PROTOCOL: Bilateral Humerus)**

For this case, the image acquired included the full length of both the pathologic humerus and the contralateral (healthy) one. This allows the healthy humerus to be used as a reference in the subsequent planning steps.

The basis for digital surgical planning is a high-quality computed tomography scan with clear and well-defined bone edges. These features are essential for the accurate design of customised instruments and implants.

This document describes the protocol for bilateral humerus CT.

**Recommendations**

The X and Y centres must not be adjusted between scans, nor should the table be raised or lowered between slices. The scan must be done with the same field of view and reconstruction centre.

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**Acquisition**

| | |
|---|---|
| **Topogram** | Humerus: from the scapula to the elbow, including the entire humerus. |
| **Field of View (FOV)** | Adjust the FOV to ensure that no anatomical region is excluded, making sure the entire arm is included. |
| **Matrix** | 512 x 512 |
| **Detector collimation** | 0.625 mm. Continuous slice increment |
| **Pitch** | ≤ 1 |

| | |
|---|---|
| **kVp** | 90-120 if the patient is obese, elderly, or has metallic components. |
| **Automatic exposure control** | Enabled |
| **Rotation Time** | ≤ 1s |

**Reconstruction**

| | |
|---|---|
| **Multiplanar Reconstruction (MPR)** | Reconstruction in all three planes of the complete study |
| **Reconstruction algorithm** | Soft tissue/moderate algorithm. Do not use the bone algorithm. Use a single window. |
| **MPR Cutting Thickness** | 0.625 mm |

**Acquisition settings (add without modifying the original ROI)**

| Parameter | Recommended | Notes/Justification |
|---|---|---|
| **Region** | Both humeri in full (from the humeral head to the distal condyles). Include the elbow if distal metallic material is present. | Prevents implant truncation. |
| **kVp** | 140 kVp (fallback 120 kVp) | Reduces beam hardening in metallic material. |
| **mA / AEC** | Automatic, with an upper limit +20–30% above standard | Compensates for increased noise due to MAR/high kVp. |
| **Rotation time** | 0.5–1.0 s (preferably 0.5 s) | Minimises motion artefacts. |
| **Pitch** | 0.7–1.0 (recommended 0.8) | Balance between coverage and resolution. |
| **Collimation / Slice** | ≤ 0.625 mm | Isotropy for MAR and 3D |

| | | |
|---|---|---|
| **thickness** | | reconstructions. |
| **FOV** | Include both humeri in full. | Prevents the prosthesis from being positioned at the detector's edge. |
| **Patient Position** | Supine, arms in a neutral position, centred with respect to the isocentre. | Proper centring of metal reduces asymmetric streak artefacts. |

**Always generate paired series with and without MAR.**

- □ **Reference (without MAR): Soft/moderate Kernel, FBP or light IR; 0.6 mm slices / 0.4 mm increment.**
- □ **MAR enabled:** Soft/moderate Kernel + Manufacturer's Algorithm (iMAR / O-MAR / Smart MAR / SEMAR).
- □ **DECT / Spectral (if available):** VMI 100–140 keV (save at least 100, 120 and 140 keV); consider 70 keV for soft-tissue assessment if artefact saturation is absent.
- □ **3D Volume (Planning):** Serie without MAR, isotropic 0.6 mm, intended for STL export.

**Post-processing and verification**

- □ Review using bone and soft tissue windows; confirm cortical continuity near the metal.
- □ If streak artefacts persist, increase the keV in VMI (120 → 140Kev) and/or compare with non-MAR series.
- □ Confirm implant centring and absence of truncation before sending to PACS.
- □ ALWAYS export STL from the non-MAR series (MAR may alter geometries).

**Console protocol sheet**

Name: ORTO_[HUMERUS_BILAT]_MAR

kVp: 140 (fallback 120)

mA (AEC): ON, limit +20–30%

Rotation: 0.5–1.0 s

Pitch: 0.8 (≤1)

Collimation: 0.6 mm (recon 0.6 / inc. 0.4) Kernels: B40s (soft) + B70f (bone) Series:

1) Standard IR (B70f)
2) MAR ON
3) VMI 100–140 keV (if DECT)
4) 3D export (without MAR)

FOV: 140–160 mm centred between both humeri