

Mathematical Optimization of Acetabular Cup Positioning Using Genetic Algorithms and Convex Programming to Minimize Post-Arthroplasty Impingement and Dislocation Risk

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INTRODUCTION:

Malpositioning of the acetabular component remains a major contributor to mechanical failure after total hip arthroplasty (THA), particularly due to prosthetic impingement and instability. Traditional safe zones for cup orientation, such as those proposed by Lewinnek and Callanan, do not account for individual anatomical and kinematic variability, resulting in persistent complication rates despite apparent geometric correctness.

Objective:

To develop and validate a hybrid optimization pipeline integrating genetic algorithms (GA) and convex programming to identify patient-specific acetabular cup orientations that minimize biomechanical risks associated with impingement and dislocation.

METHODS:

Design and Setting:

Prospective simulation-based modeling study using CT-based 3D reconstructions of 20 patients scheduled for primary THA. The study was conducted in a virtual biomechanics simulation environment validated for kinematic and geometric accuracy.

Methods:

Each patient underwent segmentation of pelvic anatomy from preoperative CT scans. A global optimization routine using GA generated 200 candidate angle pairs (inclination, anteversion) per subject, guided by a cost function penalizing impingement, reduced range of motion (ROM), poor bony coverage, and edge-loading. The best candidates were locally refined using sequential quadratic programming (SQP), constrained by anatomical morphology. Outputs were evaluated via forward kinematic simulation to assess ROM, impingement probability, acetabular coverage, and jump distance.

RESULTS: Optimized configurations achieved significantly improved biomechanical profiles compared to traditional alignments. Internal rotation at 90° flexion increased by +8.3° ($27.4^\circ \pm 3.6^\circ$ vs. $19.1^\circ \pm 4.1^\circ$, $p < 0.001$); total impingement-free ROM improved by $21.7\% \pm 4.9\%$. Mean acetabular coverage increased to $91.2\% \pm 3.1\%$, with none falling below 85%. Posterior jump distance, a surrogate for dislocation resistance, improved by +3.7 mm ($p = 0.002$). The average optimization runtime was <3.5 minutes per case, supporting real-time clinical use.

DISCUSSION AND CONCLUSION:

This patient-specific optimization model produced superior implant orientations compared to static safe zones, yielding improved ROM, coverage, and mechanical stability. The pipeline is computationally efficient, anatomically grounded, and compatible with robotic THA platforms, making it a strong candidate for integration into future precision arthroplasty planning systems.

Keywords:

Total hip arthroplasty; acetabular component; impingement; dislocation; optimization; genetic algorithm; convex programming;

biomechanics;

robotic

surgery.

Outcome Measure	Traditional Positioning	Optimized Positioning	Mean Difference	p-value
Internal Rotation at 90° Flexion (°)	19.1 ± 4.1	27.4 ± 3.6	+8.3°	<0.001
Impingement Probability >90° Flexion	0.41 ± 0.08	0.18 ± 0.05	-0.23	<0.001
Acetabular Coverage (%)	83.6 ± 5.7	91.2 ± 3.1	+7.6%	<0.01
Posterior Jump Distance (mm)	9.8 ± 1.9	13.5 ± 2.1	+3.7 mm	-0.002
Total Impingement-Free ROM (°)	165.4 ± 9.3	201.2 ± 7.5	+35.8°	<0.001

Table 2. Summary of Quantitative Outcomes

