Validation of a Hip Stem Implantation Algorithm to Quantify Surgeon Control Over Anterior Femoral Offset

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INTRODUCTION: Optimizing anterior femoral offset (AFO) is critical for total hip arthroplasty (THA) outcomes. Surgeons commonly adjust stem version and flexion to influence head center location, particularly with cemented stems. However, surgeons' actual control over femoral stem positioning remains poorly quantified, and the degree of achievable control likely varies with stem geometry, bone anatomy, and bone quality. Previous studies have not systematically characterized these relationships across diverse patient populations and implant designs. Hence, this study developed and validated a virtual stem implantation algorithm to quantify surgeon control over AFO across varied anatomical and stem design parameters. This validated model enables investigation of how different surgical philosophies (e.g., restoring native head center, altering AFO, or maximizing implant fit) influence hip mechanics.

METHODS: Eight fresh-frozen pelvis-to-toe cadaveric specimens (15 hips; one hip excluded due to damage) underwent bilateral THA (CORAIL cementless stems, collared & collarless variants, JnJ MedTech) performed by two experienced surgeons to avoid single-surgeon bias. Surgeons independently selected stem size and collar type based on their clinical experience and assessment of bone anatomy. Pre-operative CT scans were acquired to capture native bone geometry, while post-operative optical scans documented final implant positioning. Bone and implant geometries were digitally registered to establish ground truth stem alignments for algorithm validation. Native femur models were segmented from the CT scans. CT Hounsfield unit values were standardized using a calibration phantom. The intermedullary canal was identified by thresholding voxels below 200 HUs within the bone geometry (Fig.1), considering that bone tissue below 200 HU lacks sufficient mechanical integrity. The initial canal boundary was expanded by 1/2 pixel (0.45mm) to account for the gradual density transition between cancellous bone and cortical walls. For each specimen, a virtual femoral neck osteotomy was performed using a custom MATLAB script. The corresponding stem (matching experimental size and design) was initially aligned to the canal axis with the stem centered in the calcar (Fig.1). Latin Hypercube Sampling was used to generate 20,000 distinct alignments by perturbing all six degrees of freedom. Perturbation ranges were determined based on literature data to cover all clinically reasonable stem orientations. Valid alignments were defined as configurations that avoided canal penetration exceeding 0.8mm (determined from experimental observations) while maintaining the stem neck within the inner wall of the calcar resection. All valid alignments were recorded, and the configuration closest to the actual stem position was identified. All acceptable femoral head center locations were calculated and analyzed.

RESULTS: The virtual implantation algorithm successfully predicted experimental stem alignments for all specimens (Fig.2b). The average differences between experimental and closest predicted stem orientations were 2.3±0.9mm across all 15 specimens. For each specimen, the femoral head centers of all valid alignments formed a conical distribution (Fig.2a), with the experimentally achieved head center consistently positioned along the medial boundary of this region (Fig.3a). Notably, all predicted acceptable alignments were proximal to the native head center in 9 of 15 specimen (Fig.3a), and all experimental alignments resulted in a superiorly positioned femoral head. The acceptable alignment regions consistently accommodated more AFO compared to posterior offset (Fig.3b). Likewise, 13 of 15 stems were implanted with anterior femoral offset (mean 5.2±5.8mm) by the surgeons, with 8 of 15 stems exceeding 3mm.

DISCUSSION: The positioning of all experimental stem alignments along the medial boundaries of the predicted valid alignments verifies that the algorithm accurately defines the envelope of potential alignments. The experimental stem alignments may also indicate that only alignments along the boundary are stable, whereas alignments on the interior of the conical region are unstable due to reduced cortical contact. The native head center lying outside the acceptable alignment region may indicate that an oversized stem was chosen to achieve stability, which negated the ability to restore the native femoral head center. Moreover, the asymmetric alignment envelope in the sagittal plane indicates that the femoral anatomy is biased towards AFO in the studied population. These directional limitations quantify realistic boundaries of surgeon control over femoral stem orientation, providing essential parameters for computational models and evidence-based surgical planning.

SIGNIFICANCE: The validated algorithm enables evidence-based assessment of implant selection and surgical planning, while also providing a computational platform for developing new implant designs that better accommodate anatomical constraints and optimize patient-specific outcomes.

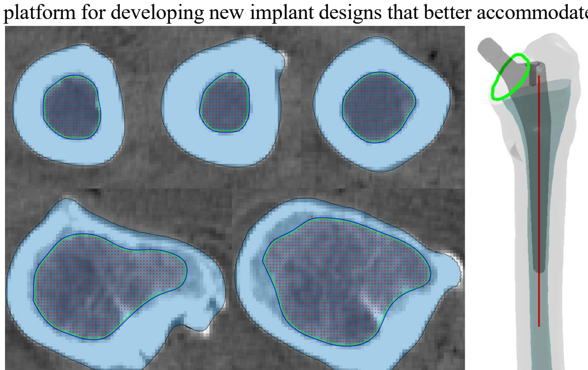

Fig.1: (Left) Intermedullary canal segmentation. **(Right)** Virtual femoral neck osteotomy and the initial hip stem alignment.

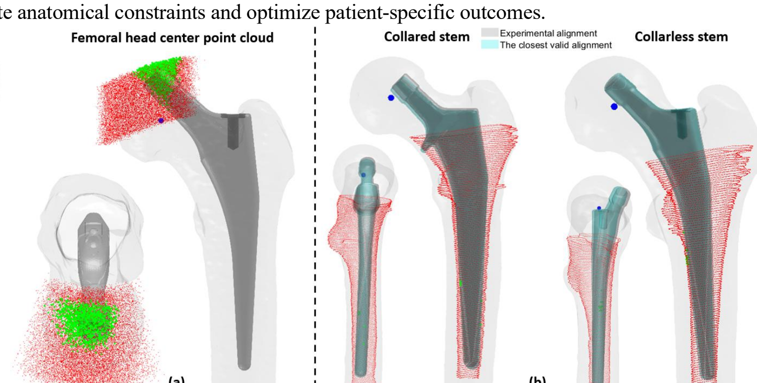

Fig.2:(a) Femoral head centers for all assessed alignments (red dots) and valid alignments (green). **(b)** Experimental alignment and closest prediction examples for different designs.

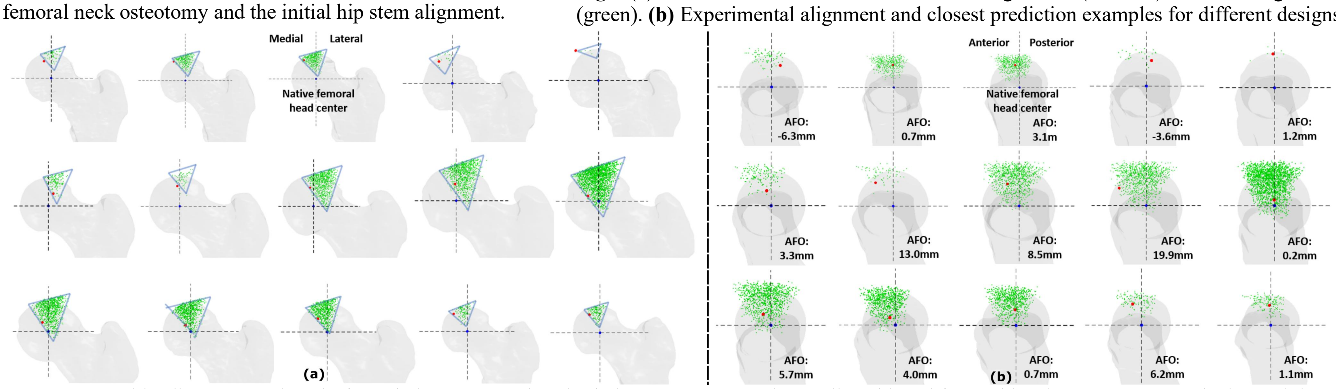

Fig.3: Acceptable alignment regions in frontal view **(left)** and sagittal view **(right)**. Experimentally achieved femoral head centers were marked as red dots.