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Automated analysis of femoral over-/underhang and bone coverage of OTS TKA implants

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Abstract

Implant overhang in total knee arthroplasty is associated with adverse effects with regard to postoperative pain and function, whereas implant underhang or bone undercoverage has been linked to increased risk of bleeding and osteolysis. To determine the suitability of different standard implant systems for a certain population, an automated analysis of overhang, underhang and coverage would be favorable. Therefore, we developed an automated framework for femoral implant interface fit evaluation. To evaluate this framework, we used surface models of 433 cadaver knees and of one specific femoral implant size. An analysis of the bone-implant interface fit was performed for all knees for which the available implant size was selected on the basis of the knee's size. The analysis involved the orientation of bone and implant via reference points, the virtual resection of the bone, and the derivation and comparison of bone-implant interface contours. Implant over-/underhang was evaluated for the entire contour and in specific zones (defined in the literature). Bone coverage was calculated for the entire interface. A good agreement with the literature with regard to mean values and ranges of over-/underhang was found. Limitations include the restriction to one specific implant system and size. Future analyses should focus on different implant sizes and systems as well as on the assessment of the tibial component.

1 Introduction

The fit of the bone-implant interface in total knee arthroplasty (TKA) has been reported to be of high relevance. Implant overhang is associated with an increased risk for pain and reduced range of motion postoperatively (Mahoney and Kinsey 2010; Bonnin et al. 2013). Implant underhang (undercoverage of the bone) has been linked to bleeding and osteolysis (Culler et al. 2017; Hitt et al. 2003). Therefore, a comprehensive preoperative assessment of implant over-/underhang and bone coverage is important, in order to identify cases at risk for poor outcomes. Several studies have evaluated femoral over-/underhang through intraoperative measurements (Chung et al. 2015; Mahoney and Kinsey 2010; Sharma et al. 2017), which is, however, time consuming. In addition, intraoperative data are subject to variability for example, through differences or errors in manual measurement and/or surgical technique. Dai et al. (Dai et al. 2014) manually planned virtual implant positioning for 277 knees and performed an over-/underhang assessment based on this planning. In doing so, they addressed the limitations of the intraoperative measurements; however, evaluating over-/underhang only in a specific zone. In a previous study by our research group, an analysis of a database of 85,143 cases showed a population coverage of almost 85%, for an exemplary implant setup of 12 optimized implant sizes and error bounds of ±1.5 mm for anteroposterior (AP) and ±3 mm for mediolateral (ML) size fit (Grothues et al. 2022). While only the total AP and ML dimensions were considered in this analysis, since they are regularly used for implant size selection, over-/underhang may occur along the entire bone-implant interface contour and should therefore be analyzed comprehensively. Furthermore, for processing large databases, an automated positioning of the implant components would be favorable. With such an automated analysis, the performance of different implant systems regarding interface fit for specific populations could be compared.

Therefore, the aim of this study was to develop an automated approach for positioning, resection planning, and full interface contour fit assessment, and to evaluate the robustness of the proposed method by analyzing a large data set.

2 Materials & Methods

Surface data, coordinates of hip and ankle joint center, as well as side information of 433 cadaver knees were available. With regard to the implant system, we used available size information and for a single size also the 3D surface model, available in the Grand Challenge Competition dataset presented by Fregly et al. (Fregly et al. 2012). The implant surface model was processed, the backside was analyzed regarding respective cutting planes, and the outer contour was derived.

An automated processing of bone models was implemented. The respective workflow is depicted in **Figure 1**. First, the femur coordinate system was aligned with the mechanical axis. Afterwards, the bone's AP height and condylar ML width were measured. For the AP height, the distance between the anterior cortex and the most posterior point in AP direction was measured. For the sizing, two millimeters of estimated cartilage thickness at the posterior condyles were added (Omoumi et al. 2015; Wernecke et al. 2016), with the goal of recreating the physiological articulating morphology. The condylar ML width was measured 10 mm above the most distal point of the condyles, as the distance of the most medial and most lateral condylar point in ML direction. The bone's size was then compared with the implant size information. Due to its high functional relevance, we prioritized the AP size fit. Maximum deviation in AP was set to 3 mm overall. With regard to ML fit, solely a maximum deviation of 6 mm was set, to limit maximum overhang on each side to 3 mm, as suggested by Mahoney et al. (Mahoney and Kinsey 2010). If the size with available implant surface data was selected, an analysis of bone-implant interface was performed. First, the implant was positioned with regard to the femur based on anterior referencing. After positioning, the femur was virtually resected based on the implant's cutting planes. Then, the outer contour of the bone was derived and compared with the implant contour. The contours were also displayed in a developed view in 2D (**Figure 1 C-D**), to enable a better visualization of over-/underhang, coverage and respective localization. Implant over-/underhang was evaluated over the entire contour, and in specific zones, defined by Bonnin et al. (Bonnin et al. 2013) and by Dai et al. (Dai et al. 2014). Bone coverage was assessed for the entire interface. After the automated analysis, the first author reviewed the implant positioning, bone resections and over-/underhang evaluation for all processed cases.

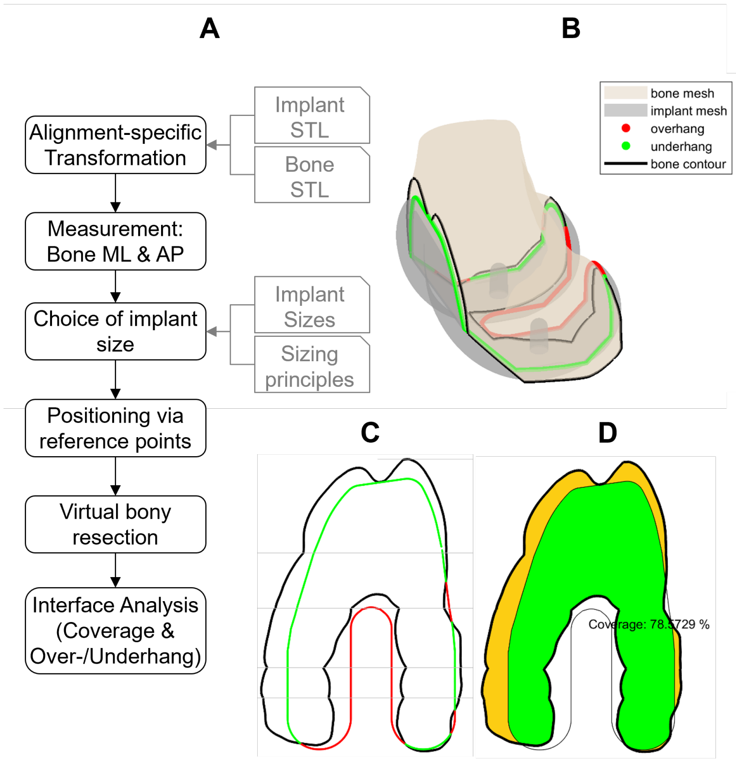

Figure 1: **(A)** Workflow of the over-/underhang analysis. Exemplary results: **(B)** Over-/underhang visualized together with implant and bone mesh in 3D. **(C)** Over-/underhang and **(D)** coverage visualized together with bone and implant interface contour, in a developed view in 2D.

3 Results

For 138 femora (31.9%), the implant size with surface data available was selected. Of those, 125 bones could be processed without errors. Two cases were excluded based on visual inspection. For all others implant positioning, bone resection and interface fit evaluation were approved by the first author. The visualizations of the over-/underhang and coverage analysis for an example case can be found in **Figure 1 B-D**. The mean contour deviation of the entire contour was 1.0 mm of underhang. The mean absolute contour deviation for the entire contour was 3.6 mm. Further quantitative results of the over-/underhang analysis in specific zones can be found in **Table 1**. Maximum underhang in the zones ranged from 6.8 mm to 13.2 mm. Maximum overhang ranged from 6.1 mm to 11.8 mm (**Table 1**). A mean bone coverage of 89.9 % (range: 78.4% -98.4%) was found.

Table 1: Quantitative results of the automated over-/ underhang analysis.

	Zone 1 (Bonnin2013)	**Zone 2** (Bonnin2013)	**Zone 3** (Bonnin2013)	**Zone Dai** (Dai2014)
Mean deviation in zone	0.7 mm overhang	5.2 mm underhang	4.6 mm underhang	3.7 mm underhang
Maximum underhang	6.8 mm	12.7 mm	13.2 mm	12.4 mm
Maximum overhang	11.8 mm	6.1 mm	6.8 mm	8.0 mm

4 Discussion

An automated assessment of femoral implant over-/underhang was successfully implemented and tested with a large database of knee surface data. Similar to the results of Bonnin et al. (Bonnin et al. 2013), wide ranges of contour deviation per zone were seen in our study. In addition, we also found that in zone 2 and 3 the implant tended to be smaller relative to the bone, compared to zone 1. Bonnin et al. (Bonnin et al. 2013) reported a mean contour deviation of 2.2 mm overhang in zone 1 and of 2.2 and 3.2 mm underhang in zone 2 and 3. In our study we found slightly lower mean overhang in zone 1 (0.7 mm), and higher levels of underhang in zone 2 (5.2 mm) and zone 3 (4.6 mm). The differences may be explained by the different aspect ratio of the two implant systems used. Bonnin et al. (Bonnin et al. 2013) used the *HLS-Noetos* implant components (Tornier SA, Montbonnot, France) whereas we used surface information from the *Sigma* Implant system (Depuy Synthes, Raynham, MA, US). The *HLS-Noetos* femoral component has a mean aspect ratio (ML/AP) of 1.11, whereas for the *Sigma* it is 1.05. This difference in design seems to have led to higher underhang in our study. Dai et al. (Dai et al. 2014) analyzed different implant systems and found that the *Sigma* and the *Triathlon* implant systems exhibited the highest amounts of underhang. For the size, which was also analyzed in our study, a mean contour deviation of ~4 mm underhang and a range of ~12 mm underhang to ~3 mm overhang was reported by the authors. Similar results however with higher maximum overhang were seen in our study (mean: 3.7 mm underhang, range: 12.4 mm underhang to 8.0 mm overhang). To the authors knowledge, there are no studies reporting quantitative results on femoral bone coverage in TKA. In our study, an average of 10% of the femoral surface was not covered by the implant, although optimal sizing was ensured with a maximum deviation in AP of 3 mm and in ML of 6 mm.

The study involved limitations. First, a 3D surface model of the OTS implant was only available for one implant size. The robustness of the method with regard to other sizes and implant systems needs to be evaluated in the future. Second, surgical plans are not always exactly met for example, due to required intraoperative adjustments. Hence, the virtual planning is theoretical. Actual implant position and resulting over-/ underhang and coverage may slightly differ from the one calculated during planning. However, for an objective evaluation of different implant system designs, an automated virtual planning has the advantage of being more time-saving and having less unknown variation. Finally, the resulting visualizations were only reviewed by the first author. In the future, additional (clinical) experts should review the visualizations and results.

A comparison of different OTS implant systems with regard to mean over-/underhang and coverage supports an objective assessment of their suitability for a specific population. Thereby, this analysis could also support the implant selection and planning process. Furthermore, the patient-specific decision making between for example, different OTS designs and/or a patient specific implant design could be supported. In addition, similar database analyses could identify critical areas of a specific implant system, with high over-/underhang, which could be addressed in a design optimization. Finally, respective analyses may also serve as a verification method for design optimization measures. In the future, also the tibia (and patella) should be included in the automated interface fit analysis to fully evaluate bone interface fit in TKA.

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