Automatic Fitting of Custom Femoral Stem Prostheses: 
Ten years of Research and Clinical Experience

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Abstract – This presentation provides a review of our approach to custom total hip replacements including principles of design, instrumentation and technique. We focus on the fitting of the stem from CT data and we show how strain constrains can drive a 3D deformable shape estimation of the stem, the basic shape being a parametric generalized cylinder.

I. Introduction

The purpose of this paper is to describe a fully automatic computerized process for the design and manufacturing of custom femoral stem prostheses. We started custom design in 1982 following 3D reconstruction of the medullary canal from radiographic projections [1], [2]. From 1985, our investigation was performed directly from CT data, [3], [4].

Custom-stems are made to improve long term results in endoprosthetic for younger patients. This is motivated by the relatively large number of loosening noted with standard implants. However, the definition of proper fit leads to controversies. In fact, most modern custom stem designs attempt to maximize canal fit an fill, in order to optimize both axial and rotational stability and minimize stress shielding [5]. Trying only to fill the proximal cavity is not a sufficient criterion, as it will lead to non predictable force transmission. So, our objective has been also to take into account a 3D valued-map which indicates the relationship between prosthesis geometry and proximal femoral strain distribution. For each digitized point of the femoral wall, this map gives a value which enforces the priority areas of contact. Then, the fitting is performed under the constrains induced by the map.

The whole process needs four steps: a sequence of hip CT images is obtained according to a prescribed protocol; each image is processed to extract a sampling of the inner contour of the bone section; from these samples, the optimal shape of the stem is computed under constrains; the numerical shape is entered into a computerized numerically controlled machine, and the implant and its rasp are milled.
The optimal shape construction is the keystone of this process, and is detailed in the next section.

II. Method

Let us emphasize how much the individual medullary canals varies in shape and size, from patient to patient. This shape can be seen as a random surface and so, our problem is typically a statistical one. The classical approach consists in finding a generic parametric model and then estimating its parameters $\theta$ given the CT data $g$. Our aim is to determine by adaptive smoothing a parametric shape which fits the data at hand.

At first glance, several classical methods could perform such a smoothing. However the stem shape must satisfy several constrains that these methods do not take into account. The first constraint is obvious but difficult to satisfy: the stem must be surgically insertable in the canal and fit in tightly. Next, the shape must be of simple geometry while respecting the canal features and satisfying a set of local constrains, i.e. the map, which defines press-fit zones between the stem and the medullary wall.

A generalized cylinder $\omega$ is chosen as a model for the stem. By definition, this is a 3D curved axis on which closed curves develop perpendicularly and continuously, [6]. Here, we cancel the hypothesis of perpendicularity. The fitted generalized cylinder, say $\widehat{\omega}$, is the result of deformable shape estimation [7], [8]: starting from an initial estimate $\widehat{\omega}_0$, the shape is iteratively re-estimated until the local constrains are approximately satisfied.

Near the greater trochanter, the canal boundary can be very erratic while on the other cross-sections, it looks like an ellipse.

We adopt an ellipse to model each $z$ cross-section curve: $\forall z \in [z_1, z_n]$. The ellipse parameters - centers $(x, y)$, axes $(d, D)$ and angle $a$ - are modelized by parametric spline functions. $\widehat{\omega}_0$ is obtained by least-squares as described in [3], [4]. The least-square criterion constructs a "smooth version" of the canal which does not respect the constrains. Then, the deformable shape estimation gives a sequence of generalized cylinders $\{\omega_k, k = 1, 2, \ldots \}$ which converges to a local minimum of a specified "energy" $U(\omega, g, \theta)$, and gives at the same time an estimate of $\theta$. $U$ is minimized when the constrains are satisfied. In the next forthcoming version of our software, the deformation process will relax the elliptical hypothesis on the cross-section above the lesser trochanter. This whole fitting algorithm takes 15 seconds on a Spark station 2.

III. Results and conclusion

Theses prostheses are commercially available ("Morpho-Adaptée" prosthesis, Médinov, France) and about two hundreds hip replacements are now accomplished per year. Here, many important remarks should be developed. The press-fit map is generally fixed but the user can change its configuration. Such a simplified map is for instance:

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where the symbols - , 0 and + stand for particular values. After fitting, these constraint values are globally verified as it can be seen on the fitted values. Our automatic design respects also the natural femoral torsion by controlling it through the fitting of the generalized cylinder axis to the natural femoral
"axis". Let us do a last remark. Although the raps has the exact shape of the prosthesis, and the shape is smooth, the cross-sections of the resulting rasping cavity do not look exactly like the contour samples. This drawback is common with all this kind of methods, and one can ask after implementation: are the stains closed to our prior knowledge on which the stem is made?

References


