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Mock-up in hip arthroplasty pre-operative planning

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The correct estimation of stem boundary conditions in hip arthroplasty cannot be performed simply by subtracting the prosthesis volume from the bone volume: the stem implant path needs to be taken into account. Digital mock-up is a technique commonly applied in the automotive field which can be used for this aim. Given a certain femur, a stem, and an implantation path, the volume of the removed bone stock can be evaluated, as well as the final contact area between the bone and the stem, and, section by section, the residual cortical bone thickness. The technique proved to be useful: if the stem implant path is not considered, the removed bone stock volume can be underestimated up to 6%, while the contact area extension can be overestimated up to 28%. On the whole, a new methodology has been set up and tested, which can be usefully employed to accurately establish stem boundary conditions in the pre-operative planning stage, and in order to perform a reliable structural stress analysis. The methodology implemented here by experienced researchers can be made available to surgeons, setting up an apposite software suite.

Key words: *hip stem, primary stability, finite element method, bone-implant interface*

1. Introduction

Hip prostheses can belong to easily implantable devices or to “more demanding” ones; the press-fit prostheses and the cemented prostheses belong to the first group: no specific skills or training are required. On the contrary, more peculiar prostheses are being sold where an elastic foundation of the prosthesis on the bone is being sought, and a minor resection of the femur neck is needed; a more demanding surgical technique is required here which hampers the large diffusion of these prostheses. In the last case, it becomes even more important to design software and hardware tools which can support the surgeon.

A personalized pre-operative planning, which means the design of an arthroplastic surgery on a specific patient, has been often supported through numerical and experimental techniques imported from classic engineering fields, to specific medical activities: reverse engineering methods have allowed a 3D reconstruction of the joint to be realized from CT images (Adam et al. [1]) or ultrasound (Doctor et al. [2]) whenever they are available or from X-rays (Zanetti et al. [3]) in all other cases; databases can be used to store different stem models in different sizes (Lattanzi et al. [4]); structural analyses can be performed on the whole biomechanical system (Kerner et al. [5]), eventually taking into account bone remodeling (Kerner et al. [5], Lengsfeld et al. [6], Nowak [7]); virtual surgery can be simulated on silico (Noble et al. [8], Sariali et al. [9], Świątek-Najwer et al. [10]); rapid prototyping allows physical models to be obtained where a less experienced surgeon can try to perform a given implant, shortening the classical learning curve and as a benchmark for a proper use of robots.

The engineering methodology considered in this work is “digital mock-up” and is commonly employed in the automotive and in the aeronautic fields (Drieux

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et al. [11], Wang [12]): it allows one to study a complex relative movement between two rigid bodies, in order to calculate contact areas, clearance, interference; it can be used in the case of hip arthroplasty in order to establish an optimal trajectory for the implant of the stem component. An innovative aspect of this study is considering that a reliable estimation of stem –bone contact areas and residual cortical bone thickness cannot be obtained simply by subtracting the prosthesis volume from the bone volume: the implant trajectory is fundamental in order to avoid not conservative estimates of these entities which play a fundamental role in the transmission of loads from the prosthesis to the bone.

The aim of this work is the application of digital mock-up as a means of assessing the influence of the trajectory along which the prosthesis (or, even before, the tool which prepares the stem seat) is implanted, on the extension and location of final contact areas and on the residual bone thickness, section by section, given different stem models and different stem sizes. Preliminary experiments performed here are aimed to assess whether this technique can be applied to hip arthroplasty in a straightforward manner, and whether the pre-operative planning could benefit from it.

2. Materials and methods

Digital mock-up needs 3D geometric models of bodies whose relative displacement is being studied; apposite software needs to be used, and output variables must be established in order to be able to compare different designs.

2.1. Numerical models

A bone CAD 3D model has been derived from the CT scan of a dried human femoral bone, in a previous work (Zanetti et al. [17]): Mimics software (Materialise, Haasrode, Belgium) has been used for volume segmentation, while Rhinoceros (McNeel, Europe) has allowed the mathematization of the external surfaces through splines.

The prosthesis CAD 3D model has been obtained from its physical model (ABG II by Stryker, 7 G/L size) using a 3D scanner (MD-20 by Roland DGA, USA) whose output is actually a cloud of points belonging to the body external surface.

2.2. Digital mockup software

CATIA v5 CAD software has allowed studying the implant phase, where the stem is inserted into the bone, using the tool dedicated to the study of mechanical couplings. An esthetic modeler (ALIAS by Autodesk) has allowed the final contact areas between the prosthesis and the bone to be precisely estimated.

2.3. The trajectories along which the stem is implanted

In Fig. 1 various possible trajectories of insertion of the prosthetic stem into the femur are shown; they have been discussed with an experienced orthopedic surgeon, they are differently oriented and they do not always follow a straight line; their envelope should include the greatest part of plausible trajectories. A trajectory is considered to be plausible if the following requisites were accomplished:

- Articular joint centre maintained,
- Physiologic limb length respected,
- Minimum cortical bone thickness guaranteed.

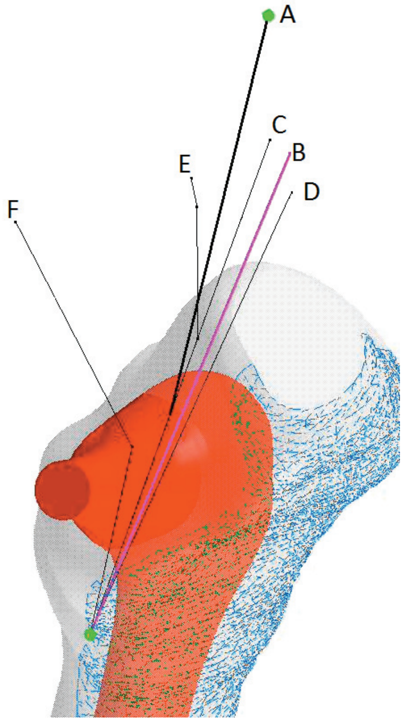

Fig. 1. Stem implant trajectories

Given a prosthesis model, the envelope of the stem along its trajectory has been calculated (Fig. 2); three criteria have been adopted in order to compare trajectories: the volume of removed bone stock, the extension and position of contact areas between the prosthesis and the bone, and the minimum cortical bone thickness on coronal sections.

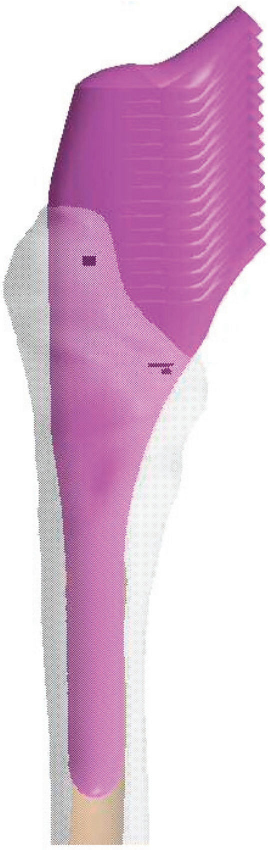

Fig. 2. Envelope of the volumes occupied by the prosthesis

In fact, according to literature, an optimum implant should preserve as much bone stock as possible (Husmann et al. [13]); it should allow a load transfer from the prosthesis to the bone through as large as possible contact areas (Howard et al. [14]), better if located proximally (in order to avoid stress shielding phenomena) (Decking et al. [15]); lastly, a minimum cortical bone thickness is needed in order to guarantee an adequate structural strength of bone component (Husmann et al. [12]).

2.4. Removed bone stock estimation

An inverted path has been assumed, where the prosthesis has been extracted from its definitive position inside the femoral canal to its initial position (Fig. 2), at 4 mm steps (step size is a compromise between geometrical details and the execution speed; it must be chosen in relation to the curvature of the trajectory): the envelope of prosthesis volumes occupied during all steps, has been intersected with the femur volume (subtracted of the medullary canal); as a result, the volume of the total removed bone stock has been obtained.

2.5. Bone-stem contact areas

The following steps have been followed:

- Intersection between the removed cortical bone stock and the prosthesis: a fictitious, very subtle volume has been obtained, corresponding to those areas where no contact took place between the prosthesis and the bone;
- the above cited volume has been exported to CATIA;
- the volume of the prosthesis has been exported to CATIA as well;
- the two volumes have been overlaid (Fig. 3);
- the surfaces which remained visible have been selected.

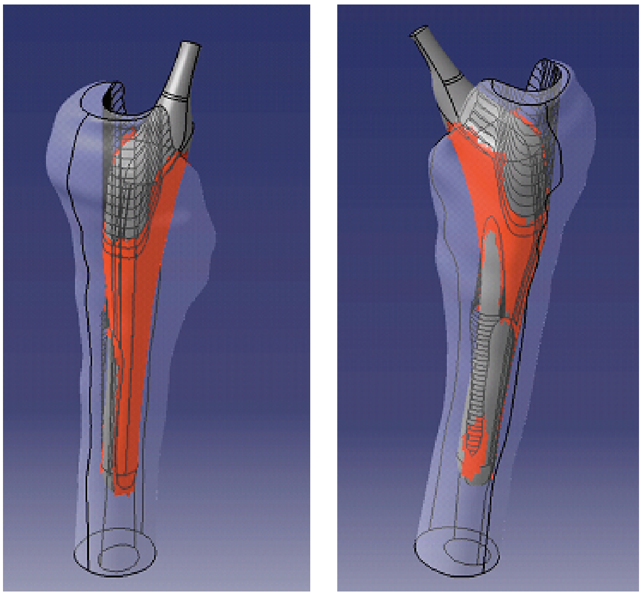

Fig. 3. Contact areas for trajectory A

2.6. Minimum cortical bone thickness check

Diaphyseal cross-sections have been analyzed in order to check the cortical bone thickness and in order to evaluate the continuity of bone–stem contact areas (Fig. 4).

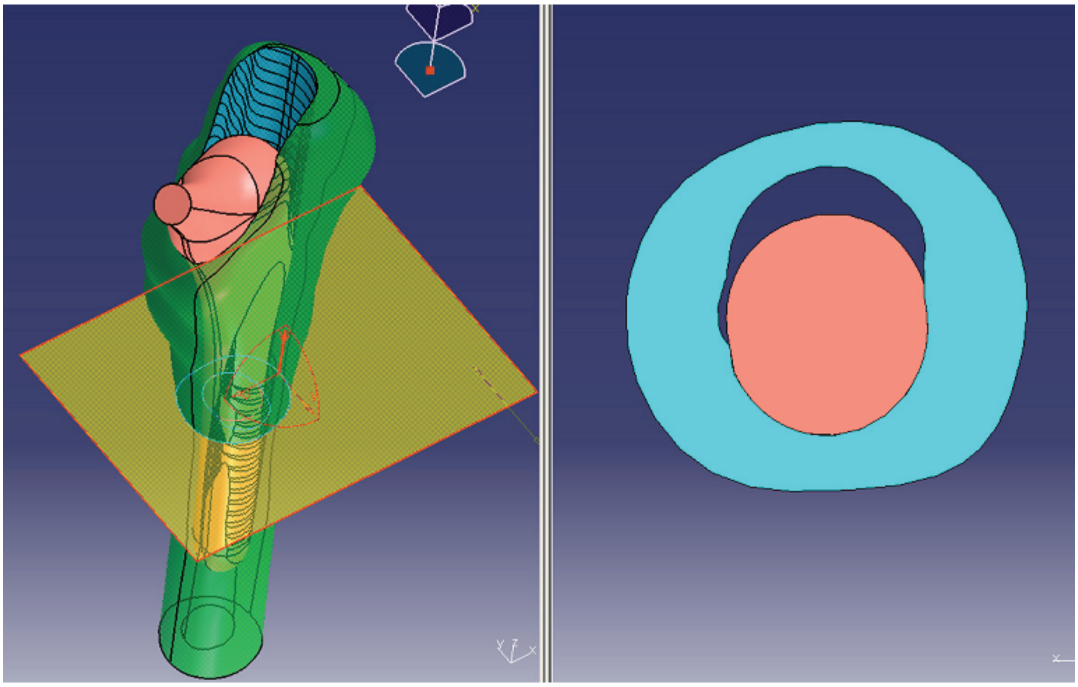

Fig. 4. Diaphyseal cross-section analysis: section by section, it is possible to establish the minimum cortical bone thickness and the extension of the contact between the prosthesis and the bone: in the section analyzed, the prosthesis (red area) touches the bone (blue area) only anteriorly, the cortical bone thickness is always good

3. Results

Once the whole procedure has been definitely set up, the analysis of a given trajectory can be performed in a very reasonable time being a question of few minutes.

The trajectories examined have produced significantly different results for what concerns the output data listed in the preceding session, even when they were very close to each other (trajectories see A and B in Fig. 1): the removed cortical bone stock (Fig. 2) has resulted to be equal to 50.42 cm^3 for trajectory A, and to be equal to 52.36 cm^3 for trajectory B, with a difference close to 4%;

Trajectory A has produced a final contact area 3.5% wider than trajectory B (Fig. 5); lastly, considering the minimum cortical bone thickness, a critical section has been identified in correspondence of the greater trochanter (Fig. 6): A has produced a minimum bone thickness equal to 2.6 mm, while B has produced a minimum bone thickness equal to 1 mm. These results prove the sensibility of the methodology, considering that trajectories A and B differed less than 2°, a value far below the accuracy of stem positioning both for manual and computer aided surgery (Petrella et al. [16], Zanetti et al. [17]).

Fig. 5. Contact area: in this case the prosthesis has no proximal contact; distally, it contacts the bone anteriorly; this boundary condition is not recommendable because it is very likely to produce stress shielding

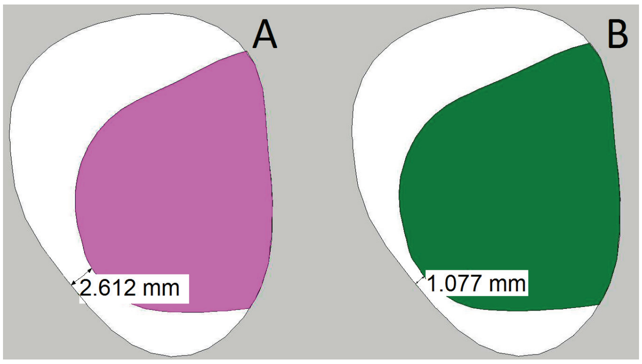

Fig. 6. Great trochanter cross-section for trajectories A (sx) and B (dx): the miminum cortical bone thickness is much smaller for trajectory B (1.08 mm against 2.61 mm)

All analyses cited above have been repeated, assuming that the prosthesis could immediately reach its final position, as simulated by most models in literature. The traditional methodology has produced consistent results for all trajectories: it systematically underestimates the removed bone volume (from –5.6% to –24.8%), it overestimates the final contact area extension (from 18.4% to 33.2%) and it overestimated the minimum cortical bone thickness (from 31.2% to 241.1%). According to literature, all these parameters play an important role in determining the failure or success of the implant (Husmann et al. [13], Decking et al. [15]).

All indicators have converged on trajectory A: compared to the worst trajectory (F) this has produced a smaller removed bone volume (–20.3%), a wider final contact area (+12.5%), and a thicker residual cortical bone (+160.0%); on the contrary, the traditional methodology would consider all trajectories as equivalent since the final stem position is the same.

4. Discussion

This work has been finalized to assess if mock-up technique can be applied to hip arthroplasty in a straightforward manner, and if the pre-operative planning could benefit from it; it is a preliminary study therefore one single bone geometry and one single stem geometry have been considered so far. However, being true that the numeric results reported here are certainly dependent on the femur geometry, the stem model, and the analyzed trajectories, nevertheless observations concerning the inaccurate estimation of removed bone volume, the final contact area and the minimum cortical bone thickness are general and remain valid for other bone–implant systems; therefore, they should be taken into account for a reliable assessment of bone–stem boundary conditions. The magnitude of estimation errors produced by traditional "subtractive" methods is related to the curvature of the implant trajectory, and to the stem shape, as can be inferred from geometrical considerations: the most critical stems are those whose transversal width does not monotonously grow (this width should be measured perpendicularly to the implant trajectory).

The criteria used here to classify a trajectory as "plausible" are certainly not exhaustive: other aspects should be taken into account such as the internal calcar septum (Decking et al. [14]) or the eventual unevenness of the hardness of the bone in the intra medullary canal, due to osteoporosis.

The methodology here introduced could be implemented by existing hip pre-operative planning software (Lattanzi et al. 2002 [3]), in order to allow a more realistic estimate of stem–bone boundary conditions. Actually, the considerations introduced here are far from being exhaustive: pure geometrical considerations have been debated; these should be integrated by structural analyses, where different stiffness and strengths are taken into account as well. Anyway, also these structural analyses need to be performed on a CAD model where boundary conditions have been accurately established, and this work is meant to contribute to this aim.

The methodology has been illustrated and tested considering 3D geometries, but the same observations developed here on volumes and areas could be replicated considering two planar views, and measuring areas and lengths, respectively. However, a 3D reconstruction would surely allow much more accurate evaluations; being true that up to now CT-Scan are reserved for severe revision surgery or deformity, in a near future they could become available also for the common patient, considering the radiation dose is noticeably diminishing (Henckel et al. [189]) and CT scanners are becoming more and more widespread; besides, also 3D reconstruction techniques based on ultrasound are likely to be available in a near future (Doctor et al. [2]).

The methodology could be usefully integrated with an automatic routine which individuates all possible trajectories, here manually established; these trajectories should be individuated taking into account the accuracy of the surgical procedure which can be optimistically estimated to be equal to ±3° (Petrella et al. [16], Zanetti et al. [3], [17]).

5. Conclusions

The results obtained have confirmed the applicability of this technique to the orthopedic field; the trajectory chosen for stem insertion has been demonstrated to play an important role in what concerns bone–implant success: it determines the amount of removed cortical bone stock, the extension and position of bone–stem contact area, and the minimum cortical bone thickness on diaphyseal cross-sections.

The methodology is able to discriminate even two very close trajectories (whose angulation differs less than 2°); it produces consistently different results when compared to the traditional approach, followed for the creation of most numerical models, where the prosthesis is assumed to reach immediately its final location: in this way a not conservative estimate of the removed cortical bone stock and of contact areas is obtained.

Referring to the pre-operative planning stage, the technique has been applied here to compare different insertion trajectories; however, it can also be a support to choose among different stem models, given the patient femur morphology.

References

[1] ADAM F., HAMME D.S., PAPE D., KOHN D., *Femoral anatomy, computed tomography and computer aided design of prosthetic implants*, Arch. Orthop. Trauma Surg., 2002, Vol. 122, 262–268.

[2] DOCTOR A., VONDENBUSCH B., KOZAK J., *Bone segmentation applying rigid bone position and triple shadow check method based on RF data*, Acta of Bioengineering and Biomechanics, 2011, Vol. 13, 3–11.

[3] ZANETTI E.M., CRUPI V., BIGNARDI C., CALDERALE P.M., *Radiograph based femur morphing method*, Med. Biol. Eng. Comput., 2005, Vol. 43, 181–188.

[4] LATTANZI R., VICECONTI M., ZANNONI C., QUADRANI P., TONI A., *Hip-Op: an innovative software to plan total hip replacement surgery*, Med. Inform. Internet Med., 2002, Vol. 27, 71–83.

[5] KERNER J., HUISKES R., VAN LENTHE G.H., WEINANS H., VAN RIETBERGEN B., ENGH C.A., AMIS A.A., *Correlation between pre-operative periprosthetic bone density and post-operative bone loss in THA can be explained by strain-adaptive remodeling*, J. Biomech., 1999, Vol. 32, 695–703.

[6] LENGSFELD M., GUNTHER D., PRESSEL T., LEPPEK T.R., SCHMITT J., GRISS P., *Validation data for periprosthetic bone remodelling theories*, J. Biomech., 2002, Vol. 35, 1553–1564.

[7] NOWAK M., *On some properties of bone functional adaptation phenomenon useful in mechanical design*, Acta of Bioengineering and Biomechanics, 2010, Vol. 12, 49–54.

[8] NOBLE P.C., SUGANO N., JOHNSTON J.D., THOMPSON M.T., CONDITT M.A., ENGH SR C.A., MATHIS K.B., *Computer simulation: how can it help the surgeon optimize implant position?*, Clin. Orthop. Relat. Res., 2003, Vol. 417, 242–252.

[9] SARIALI E., MOUTTET A., PASQUIER G., DURANTE E., CATONE Y., *Accuracy of reconstruction of the hip using computerised three-dimensional pre-operative planning and a cementless modular neck*, J. Bone Joint. Surg. Br., 2009, Vol. 91, 333–340.

[10] ŚWIĄTEK-NAJWER E., BĘDZIŃSKI R., KROWICKI P., KRYSZTOFORSKI K., KEPPLER P., KOZAK J., *Improving surgical precision – application of navigation system in orthopedic surgery*, Acta of Bioengineering and Biomechanics, 2008, Vol. 10, 55–62.

[11] DRIEUX G., LÉON J.C., CHEVASSUS N., GUILLAUME F., *From digital mock-up to virtual prototypes in the aeronautic industry*, [in:] J.J. Villanieva (ed.), Proceedings of the Fourth IASTED International Conference on Visualization, Imaging and Image Processing, Calgary, Canada: Acta Press, 2004, 701–706.

[12] WANG G., *Definition clarification and review on virtual prototyping*, [in:] D.T. Mook, B. Balachandran (eds.), Proceedings of the 2001 ASME Design Engineering Technical Conference, USA, ASME, New York, 2001, 349–357.

[13] HUSMANN O., RUBIN P.J., LEYVRAZ P.F., DE ROGUIN B., ARGENSON J.N., *Three dimensional morphology of the proximal femur*, J. Arthroplasty, 1997, Vol. 12, 444–450.

[14] HOWARD J.L., HUI A.J., BOURNE R.B., MCCALDEN R.W., MACDONALD S.J., RORABECK C.H., *A quantitative analysis of bone support comparing cementless tapered and distal fixation total hip replacements*, J. Arthroplasty, 2004, Vol. 19, 266–273.

[15] DECKING J., DECKING R., SCHOELLNER C., DREES P., ECKARDT A., *The internal calcar septum and its contact with the virtual stem in THR: a computer tomographic evaluation*, Acta Orthop. Scand., 2003, Vol. 74, 542–546.

[16] PETRELLA A.J., STOWE J.Q., D'LIMA D.D., RULLKOETTER P.J., LAZ P.J., *Computer-assisted versus manual alignment in THA: a probabilistic approach to range of motion*, Clin. Orthop. Relat. Res., 2008, Vol. 467, 50–55.

[17] ZANETTI E.M., SALAORNO M., AUDENINO A.L., *The Variability of Prosthesis Positioning and the Resulting Geometry of Coxo-femoral Joint*, [in:] D.W. Liepsch (ed.), 5th World Congress of Biomechanics, Medimond, Bologna, Italy, 2006, 177–181.

[18] HENCKEL J., RICHARDS R., LOZHKIN K., HARRIS S., BAENA F.M., BARRETT A.R., COBB J.P., *Very low-dose computed tomography for planning and outcome measurement in knee replacement. The imperial knee protocol*, J. Bone Joint Surg. Br., 2006, Vol. 88, 1513–1518.