TECHNICAL NOTE

Speedy skeletal prototype production to help diagnosis in orthopaedic and trauma surgery.
Methodology and examples of clinical applications

E. Debarre\textsuperscript{a}, P. Hivart\textsuperscript{a,*}, D. Baranski\textsuperscript{b}, P. Déprez\textsuperscript{a}

\textsuperscript{a} Artois Biomaterials Research Unit (Artois University), Civilian Engineering Research Laboratory and géo-Environment Research Laboratory (LGCgE EA 4515, Lille North of France University), IUT/GMP, 1230, rue de l’Université, BP 819, 62408 Béthune cedex, France
\textsuperscript{b} Department of Orthopaedics and Traumatology, Germon & Gauthier de Béthune Hospital Center, rue Delbecque, 62660 Beuvry, France

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Summary
As a medical imaging complement, a real 3D replica of the anatomical area of interest can be of substantial advantage in orthopaedic and trauma surgery. Unlike the 3D virtual, it makes palpable the notion of scale and volume, and apparent hidden or ambiguous details and thus enhance or facilitate the diagnosis and eventual surgical solutions. CT data of patients, in DICOM3 standard, were used for digital 3D reconstruction followed by rapid prototyping (fused deposition modelling) of acrylonitrile-butadiene-styrene (ABS) replicas of the areas of interest. Three applications were realized: osteotomy for epiphysial malunion, shoulder arthroplasty and femoral trochleoplasty. The actual size replicas (obtained in less than thirty hours) provided excellent spatial representation with estimation of available bone stock and materialization of relief. The process has proven to be appropriate (and economically reasonable), including for common cases, when it comes to complex spatial geometry and objective representation of the scale of volumes.

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Introduction
Medical imaging provides 2D views or virtual 3D reconstructions in which scale, however, is not easily judged, the third dimension is hard to discern and detail may be hidden or ambiguous, all such representations being in fact 2D visualizations. It assists the orthopaedic surgeon in selecting, planning and optimizing procedures, by identifying bone pathology and trauma, but fails to enable fine analysis of spatial relations, such as joint asymmetry and kinematics. A technique providing simple assessment of scale and volume is thus of major interest.

Rapid prototyping \cite{1} is a means of producing a 3D replica based on digital modelling, and has been applied in medicine

\textsuperscript{*} Corresponding author. Tel.: +33 3 21 63 23 55. E-mail address: philippe.hivart@univ-artois.fr (P. Hivart).

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Figure 1 From imaging to prototype: methodology. a: DICOM-3 data files (medical imagery); b: selection and digitized virtual reconstruction (example: healthy side); c: 3D replica by rapid prototyping (example: pathologic side).

since the 1990s, Petzold et al. [2], in an update of the state of the art, summed up its clinical interest in the slogan “Touch to comprehend”. The interest lies in refining diagnosis and planning or even simulating surgery, and in presenting procedures and customizing implants and/or ancillaries [3–6]. The technique is often reserved for complex pathologies, scheduled surgery or certain specific fields [7–13], due to technological limitations [14–16]; recent progress in CT, IT and prototyping, however, holds out the promise of wider use and application in more routine cases [17,18].

The present report concerns three cases using the simple technology of prototyping by fused deposition modelling (FDM) in orthopaedics and traumatology, illustrating the potential extensions of its field of application. The aim is to demonstrate the resultant facilitation of planning and to recommend a technical aid to surgery that does not impact the standard procedure or outcome.

**Material and methods**

Constructing an anatomic replica (Fig. 1) involves CT data to determine geometry, data processing (digitized reconstruction), and then rapid prototyping (replica).

Areas of interest were fine-contoured on each slice (TOSIBA Aquilion™ or GE LightSpeed VCT™ multislice helical CT system; minimum slice width, 0.5 mm; DICOM-3 standard). The contours were then compiled to reconstruct the digital envelope of the bone, using dedicated RapidForm 2006™ (Inus Technology) or Mimics™ (Materialise) software. After eliminating abnormalities and artifacts (holes, edge effects, noise), a 3D surface object was generated and converted into a standard 3D data file compatible with any CAD software (Catia™, Dassault Systèmes; Mechanical Desktop™, Autodesk; or ProEngineer™, Parametric Technology Corporation). The role of the clinician was to select or adjust the region to be replicated. At the end of the digital phase, a patient-specific virtual model was available for replica production.

The FDM rapid prototyping technique (Dimension BST768™, Stratasys) was selected for its ease of use, reasonable cost, fully self-contained operation and absence of pollution. The end-product is an object in acrylonitrile butadiene styrene (ABS, used for both the prototype and its support) that is rigid and functional and can be physically manipulated by the clinician (Fig. 2). The layer thickness (= definition) equals the strand diameter of 0.254 mm.

**Results**

The interest of rapid prototyping obviously lies in giving concrete form to the complex geometry of anatomic structures and precisely determining bone volume, by means of individualized 3D replicas. The present report assesses the technique’s application in three types of clinical case,
respectively involving osteotomy for epiphyseal malunion, shoulder arthroplasty and femoral trochleoplasty (Table 1).

**Figure 2** Rapid prototyping by fused deposition modelling (FDM, Stratasys Dimension BST760™). a: table (vertical movement); b and b’: prototype and support; c: injection head and nozzles (planar movement); d and d’: prototype strand and support strand (ABS: acrylonitrile-butadiene-styrene).

**Epiphyseal malunion**

Application of the technique in epiphyseal malunion is illustrated by the case of a 44-year-old male victim of comminutive epiphyseal-metaphyseal fracture of the proximal third of an osteosynthesized tibia (Fig. 3); a posterior medial tuberosity reduction defect required corrective osteotomy. Two replicas were produced (pathologic side and healthy contralateral mirror): (Fig. 4) and unambiguously demonstrated that the planning of complex osteotomy to correct epiphyseal malunion benefited from real-scale modelling. Palpation of the prototype enabled exact quantification of volumes (Fig. 4a), which proved very useful for determining the osteotomy lines. Prototyping is the only planning aid providing so precise a representation of malunion (benefit increasing with geometric complexity).

The contralateral replica further provided a representation of the targeted normal anatomy: a ''mirror'' prototype derived from an inverted image of the contralateral site served as a model for ''ideal'' reconstruction (Fig. 4b–c).

**Table 1** Rapid prototyping: production data.

<table>
<thead>
<tr>
<th>Clinical case</th>
<th>Epiphyseal malunion (tibia)</th>
<th>Arthroplasty (shoulder)</th>
<th>Trochleoplasty (trochlea, patella)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing time</td>
<td>2 h</td>
<td>2 h</td>
<td>2 h</td>
</tr>
<tr>
<td>Prototyping time</td>
<td>27 h</td>
<td>24 h</td>
<td>24 h</td>
</tr>
<tr>
<td>Replica height</td>
<td>200 mm</td>
<td>80 mm</td>
<td>90 mm</td>
</tr>
<tr>
<td>Volume of ABS used</td>
<td>500 cm$^3$</td>
<td>120 cm$^3$</td>
<td>300 cm$^3$</td>
</tr>
<tr>
<td>Materials cost</td>
<td>€180 pre-tax</td>
<td>€45 pre-tax</td>
<td>€120 pre-tax</td>
</tr>
</tbody>
</table>

**Bone-capital evaluation ahead of shoulder arthroplasty**

Application in shoulder arthroplasty is illustrated by the case of a 60-year-old female patient presenting with centered arthritis of the shoulder, managed by total anatomic replacement. The scapulo-humeral replica (Fig. 5) enabled excellent estimation of available bone capital, where CT suggested possible implantation problems arising from severe joint wear, by manually comparing available bone volume to the intended implant (which, moreover, did not necessarily have to be sterile). It was also possible to rehearse glenosphere and screw positioning, and all perspectives for the prototype could be manipulated, enabling joint visualization to be anticipated according to surgical approach.

Likewise, resurfacing implants could be compared in advance to the corresponding humeral replica. Traditional
CT slices may, however, be preferred for humeral head assessment in case of aseptic osteonecrosis.

Femoral trochleoplasty

Application in trochleoplasty is illustrated by the case of a 37-year-old female patient presenting with a luxating dysplastic trochlea impairing the functional results that had been obtained from a tuberosity transposition performed a few years previously.

Abnormalities in femoral trochlea geometry are varied, and determining surgical indications requires their identification on rigorous radiographic assessment complemented by CT [19]. All such data were represented in two replicas (right and left trochlea plus patella): (Fig. 6). The excessive relief of the proximal part of the trochlea was perfectly visible, and its size could be quantified with precision. “Spurs” and “double contour” were very concretely represented, greatly facilitating trochleoplasty planning.

Discussion

Surgical planning involving complex volumes (especially when idiosyncratic, as in the case of severe epiphyseal malunion) is facilitated by rapid prototyping. Any indication for bone morphology CT is a potential application, but particular benefit is found in complex osteotomy. A prototype can be sawed, screwed or glued, enabling fine simulation of postoperative results. Internal structures are reproduced as faithfully as the outer surfaces.

In malunion, the surgical approach can be limited thanks to the excellent spatial representation and the ability to actually manipulate the complex bone replica, thereby simplifying landmarking and surgical site exposure.

Separate prototypes (up to $200 \times 200 \times 300$ mm) can be assembled together to reconstitute larger anatomical areas.

A replica can be produced in less than 48 hours. This may still make the technique unsuitable in emergency traumatology, but production times could perhaps be optimized. A technician is needed for no more than 2 hours, basically to deal with digitization; the actual production requires no human presence. Technological advances are constantly reducing the time factor. Comminution and displacement do not prevent modelling of recent fractures.

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as a support structure (differentiated by color) holds the fragments together.

Modelling osteoporotic or necrotic tissue remains an unresolved issue: the texture of the prototype is never that of the actual bone, and this is to be borne in mind, especially when the technique is applied in arthroplasty.

Patients appreciate being able to see these models, which help in ensuring truly informed consent.

As rapid prototyping machines are marketed for a wide range of fields, they are not subject to the elevated costs associated with dedicated medical instrumentation; prices are thus quite reasonable, and constantly decreasing (€20,000 pre-tax for an FDM device).

New applications (in non-bone tissue) can be expected: the digital data could be derived from MRI, opening up new horizons.

Conclusion

Rapid prototyping has yet to make its mark in orthopaedic surgery. Potential applications, however, are numerous and worthy of interest in certain indications. Practically speaking, it is well-adapted to complex geometry and precise estimation of bone volume: for example, in certain kinds of osteotomy and in shoulder arthroplasty.

Objective representation of volume scale is the strong point of rapid prototyping in orthopaedic planning. It could usefully complement paraclinical assessment and traditional imaging.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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References


