J Orthopaed Traumatol (2006) 7:72–79
DOI 10.1007/s10195-006-0124-y

ORIGINAL

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Computer-aided reconstruction of hip joint in revision arthroplasty

Received: 12 March 2005
Accepted: 23 December 2005
Published online: 20 June 2006

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Abstract Geometric revision reconstruction of the hip joint of a female patient is presented. Because of extensive bone resorption and strong bone obstruction, we decided to employ a custom-made prosthesis not only in the pelvis but also in the femur. The custom prosthesis design and manufacturing processes were carried out with the aid of computed tomography (CT), a system of tomographic image processing, a computer-aided design (CAD) system and a computer-aided manufacturing (CAM) system. The process included tomographic measurements of the patient's hip joint, conversion of the CT images, geometrical modelling of the femur and pelvis in the CAD system, prostheses design, virtual simulation of the reconstructed acetabulum, determination of prosthesis matching, and manufacturing on a CNC machine. The outcome of this engineering process was a total hip arthroplasty (THA) surgical operation.

Key words Gait analysis • Prosthesis design and manufacture • Total hip replacement

Introduction

Over the last two decades, a gradual increase in the number of hip joint surgical arthroplasties has been observed worldwide. This is due, on the one hand, to changing social conditions, i.e. the ageing of the societies of developed countries, and to changes in civilization such as a more sedentary way of life and violent development of communication (high frequency collision), and on the other hand, to the rapid development of techniques in biology and tissue engineering that make it possible to elaborate and apply new solutions in hip joint implant design.

Hip joint implant loosening

Experience and observations of orthopaedic centres show that the results of arthroplasties have been continuously aggravating due to loosening of the prosthesis element. In the early days of surgical treatment of the hip joint, the problem of prosthesis element aseptic loosening was disregarded. The first observations concerned septic (inflammable) loosening of prostheses. Those papers in which the etiopathogenesis and recognition of the sterile loosening of hip implants were described appeared in the 1970s. Nowadays, the problem of treatment method is crucial and requires an orthopaedist to know about the pathomechanisms that lead to sterile loosening of the endoprosthesis [1, 2].

Progressive wear of some implant components, secondary reaction of tissues to wear debris, and faults committed during the primary operation are the most significant factors influencing implant loosening. Progressive implant wear is associated with increased pain in the operated joint and gait dysfunction. These symptoms indicate that revision arthroplasty is called for. Implant loosening, if detected early, allows the implant to be replaced without any surgical difficulty. In the case of advanced loosening, the pathological motion of implant elements and the sec-

ondary tissue reaction cause significant bone tissue loss in the pelvis and the proximal part of the femur. The degree of complication and complexity of reconstruction in such cases is considerable. In the case of extensive bone atrophy, for many years the Girdleston technique was preferred. It consisted of creating an imaginary joint by extracting the implant from the body and leaving the joint un-articulated.

The process of implant aseptic loosening has a slow and progressive character. It is associated with continuous bone tissue atrophy in the vicinity of the implant. Regardless of implant fixation technique (a cemented or cementless endoprosthesis), the diameter of the acetabulum increases as a consequence of pathological implant motion and reactive tissue destruction. The artificial acetabulum migrates upwards and, often, into the pelvis [3, 4]. Similarly, in the femur stem, the medullary canal becomes wider due to implant motion. Cortical bone tissue, which constitutes the support for the implant stem, becomes thinner, weaker and more susceptible to fracture [5].

Prostheses and techniques applied in hip joint revision arthroplasty

The staff of medical centres that perform arthroplasty operations have been looking for technical solutions which would make it possible to reconstruct the pelvis-prosthesis-femur system. A universal solution that would be applicable in every case of prosthesis aseptic loosening has not been found. The whole procedure, i.e. selection of the technique and implant, should be individually established. The number of elements which have loosened and the degree of bone resorption are the main criteria [3]. Years ago, large amounts of bone cement were applied in order to replace atrophied bone and obtain firm fixation of the new acetabulum and prosthesis stem. Clinical observations showed that after a relatively short time, implant loosening at the bone-cement interface occurred, as did femural fracture. Another solution was to apply stiff metal implants supporting the acetabulum, such as special cages and caps of the "Ω" shape, inside which the acetabulum was mounted by means of cement [6, 7]. Follow-up observations were not satisfactory in these cases, either [5, 8]. At some medical centres, cementless and cemented implants of high diameter were used with some success. However, the results indicated that such implants could be applied only in a limited number of patients [9–11]. Bi- or tri-polar acetabulum prostheses are an alternative solution used nowadays at many centres. The construction of these prostheses is such that they can be implanted even in the case of vast bone tissue atrophy in the pelvis. In cases of bone loss in the acetabulum area and the femur, solid bone allografts, originating from the femur head or pelvic bone, have been commonly utilised. The allografts were mounted into the existing bone by means of surgical screws. However, they frequently underwent a process of autolysis that led to loosening of the implant [12, 13].

Further experiences and observations showed that bone loss, occurring during the implant loosening process, can be replaced in a "biological" way with grinded bone grafts. It is nowadays accepted and the most efficient way of bone loss reconstruction in hip joint [1, 5, 8, 13–15]. Usually frozen morselised allogenic trabecular bone grafts are utilised. The bone grafts are packed tightly in the existing bone cradle. In addition to this, when structural bone loss is diagnosed, metal elements are also applied. These metal elements are, for instance, acetabulum and stem nets that can be shaped so they match the anatomical structure of the joint, as well as various kinds of cages, rings and acetabulums of complex shape [16]. The stems of revision prostheses are longer than those of standard prostheses. Revision prostheses are implanted without cement and in some cases they are alternatively stabilised at the distal part with screws in order to prevent rotational movements of the implants. Yet another type of stem construction deserves mention, namely, the modular stem. It is implanted in cases of complete bone resorption in the vicinity of the trochanters where no application of nets, rods and bone grafts is possible.

It has to be emphasised that an important prerequisite for applying the acetabulum reconstruction technique mentioned above is the possibility of firmly packing the morselised bone grafts into the existing bone and to mount an implant (net, cage) that constitutes a support for the grafts [1, 5, 8, 13–16]. In advanced cases of implant loosening where the majority of the acetabulum has atrophied, this technique cannot be used. Nor is application of rings and cages possible. Recently, application of allogenic grafts of the whole acetabulum or its major part has been a very interesting and promising line of development. Such grafts are mounted with screws after resection of the damaged bone tissue. Then, an artificial acetabulum is fixed, as in the primary operation [17, 18].

Anatomical (custom-made) prostheses of the hip joint

Another group of prostheses applied in revision operations are custom-made prostheses [19, 20]. Such a prosthesis is designed and manufactured for a particular clinical case, and its shape matches the anatomical characteristics of the patient. Custom-made prostheses are applied in revision operations, especially in cases of significant

bone tissue atrophy where fixation of the prosthesis is difficult. Application of a custom-made prosthesis makes it possible to restore the proper anatomical characteristics of the joint and its functionality. Anatomical prostheses are also used in primary arthroplasty in cases of innate joint deformation and – more rarely – when abnormal dimensions of the joint or abnormal bone properties have been diagnosed. In some complicated cases such prostheses are the only possible means of restoring joint motion over a certain range.

Nowadays, several companies offer custom-made prostheses for insertion into the femur or pelvis. In the former case, there are significant differences between models: some types differ slightly from standard prostheses while others are characterised by their complex shapes matching the medullary canal, by the spatial orientation of the neck with respect to the stem, or by various specific construction solutions. Some designs of artificial hip joint acetabulum are significantly different from the standard ones, e.g. the lower part of the pelvis is extracted and the prosthesis is fixed into the upper part.

Geometric reconstruction of the joint

A clinical case description

A 72-year-old woman was operated on due to degenerative disease of the hip joints, of an idiopathic character. The operations were performed in 1989 (the right hip joint) and in 1994 (the left hip joint). In 2001 the patient was admitted into a clinic because clinical and radiological symptoms of right hip joint prosthesis loosening had been noticed. Radiography showed asymmetrical positioning of the prosthesis neck with respect to the centre of the acetabulum, displacement of the acetabulum prosthesis, and bone tissue resorption around the prostheses, i.e. the stem and acetabulum (Fig. 1a).

During revision arthroplasty, after having removed the loosened prosthetic devices, a huge amount of degenerated bone tissue with polyethylene particles as well as vast bone resorption in the pelvis were observed (Fig. 1b). Reconstruction of the bone loss using the Slooff technique, which has been applied at the clinic, was not possible. Therefore, it was decided to leave the joint unarticulated. Due to the range and character of bone loss, after examination of the products available on the market, it was decided to design and manufacture a custom-made prosthesis – an acetabulum cage.

Custom-made prosthesis design and manufacture

The process of designing and manufacturing the acetabulum and femur prostheses was undertaken utilising computed tomography (CT), a system of tomographic image processing, computer-aided design and computer-aided manufacture (CAD/CAM) systems and a system of computer numerical control (CNC) machines. The process comprises the following steps:

- Tomographical projection of the patient's hip joint
- Conversion of the CT images
- Modelling of the pelvis and femur
- Virtual simulation of the reconstructed joint

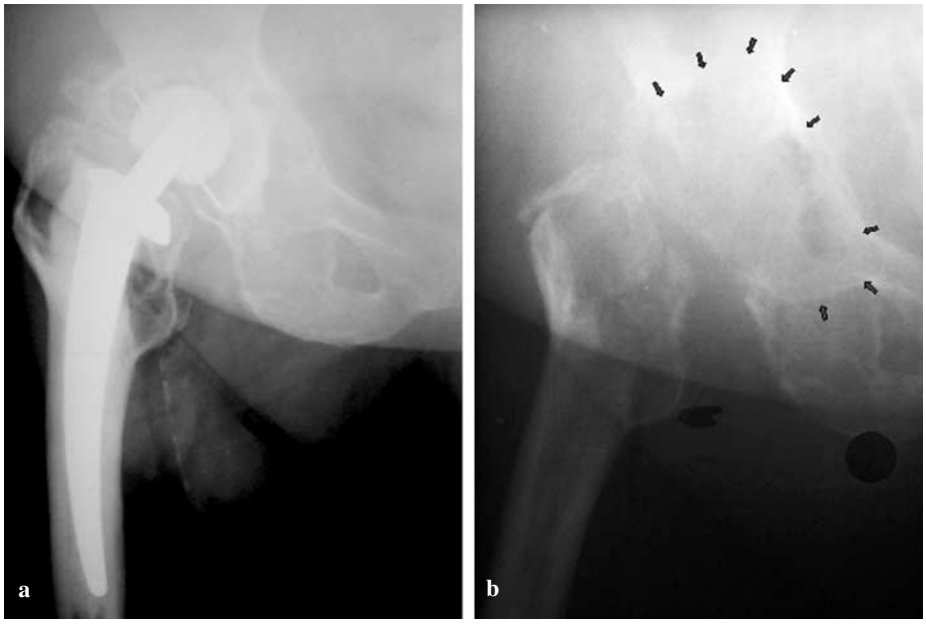

Fig. 1a, b *Radiographs of the right hip joint 11 years after arthroplasty.* **a** There is implant loosening and acetabulum destruction. **b** After prosthesis removal, an acetabulum perforation of 4 cm diameter is visible. *Arrows*, extent of bone atrophy

Fig. 2a-c *Bone contour detection in one of the CT scans*. **a** CT image. **b** Detected bone tissue of the determined radiological density. **c** Contours of the detected areas

- Design of the cage (acetabulum prosthesis)
- Elaboration of the model on a CAM system and prosthesis manufacture.

CT image processing and bone modelling

CT projection yields images of the patient's tissues in defined cross-sections (Fig. 2). In order to acquire data by means of which the bone modelling in CAD systems is possible, the CT images have to be properly processed (converted). The conversion consists of:

- Detection of tissues of defined radiological density (Fig. 2b) on the basis of the value of Hounsfield's number

$$C_T = \frac{\mu - \mu_{H_2O}}{\mu_{H_2O}},$$

where μ is the coefficient of X-ray dissipation characteristic for the given tissue.
- Detection of the contours of the defined areas in the form of curves on every scan (Fig. 2c).
- Acquisition of a coordinative description (x, y, z) of the contour curves in a format compatible with a CAD system.

As a result of CT image conversion, a description of the bone contours in each scanned layer was obtained, in the form of ordered point co-ordinates. This description was then utilised in the CAD system Pro/ENGINEER using the Pro/ScanTools module (both by Parametric Technology Corporation, Boston, USA). The curves defining the contours of the bones were approximated on the points in chosen scans and then used to generate surfaces. Finally, solid models of the pelvis and femur were created (Fig. 3).

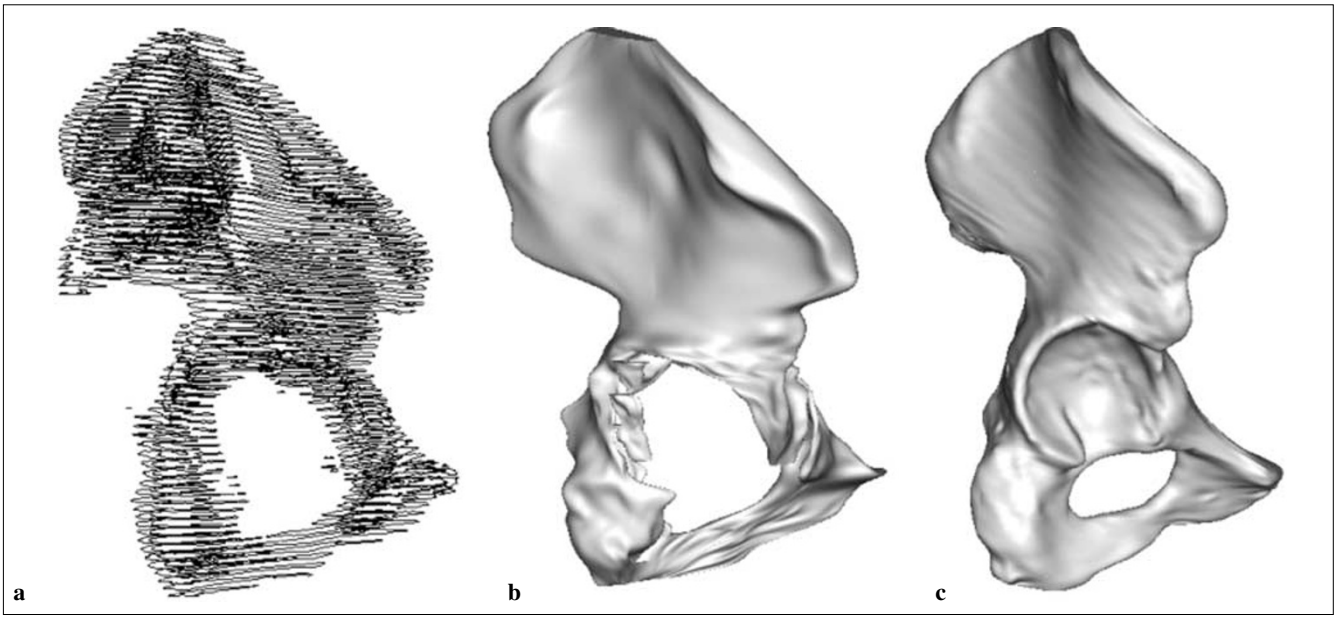

Fig. 3a-c *Pelvic bone modelling*. **a** Bone contours interpolated on the basis of CT data. **b** Solid model of the damaged pelvis. **c** In comparison with the model of normal pelvis

Acetabulum prosthesis design and manufacture

The acetabulum prosthesis was designed on the basis of the pelvis and femur models created in Pro/ENGINEER. Prosthesis construction consisted of a cage and polyethylene cup fixed with a thin layer of cement and bone grafts. The cage is to ensure proper and durable cup fixation in the pelvis and consequently to achieve the proper geometry of the joint. The shape of the cage is also important because it has to match the anatomical structure of the pelvis. This makes it possible to properly fix the cage into the parts of the pelvis where bone tissue is in good condition. For this purpose, special lateral and upper handles of the cage were designed. The possibility of adjusting the upper handle to the shape of the pelvis during the operation was preserved. In the hemispherical part of the cage, as many holes as possible were made to facilitate its fixation into the pelvis and application of bone grafts in order to enhance its stability. The orientation of the cage axis was assumed with respect to the femur position. Virtual simulation of the reconstructed hip joint is presented in Figure 4.

Due to the complex shape of the cage and the fact that it would be made only once, we decided to manufacture it on a CNC machine. The cage was made of austenitic steel 316 LVM Sandwick, in its High-N modification used for long-term implants. The processing was elaborated in AlphaCAM (Licom Systems Ltd, Coventry, UK). The manufactured cage is shown in Figure 5. An identical cage was also manufactured of duralumin. The duralumin cage was used during the operation to position and finally adjust the holders to the surface of the pelvis.

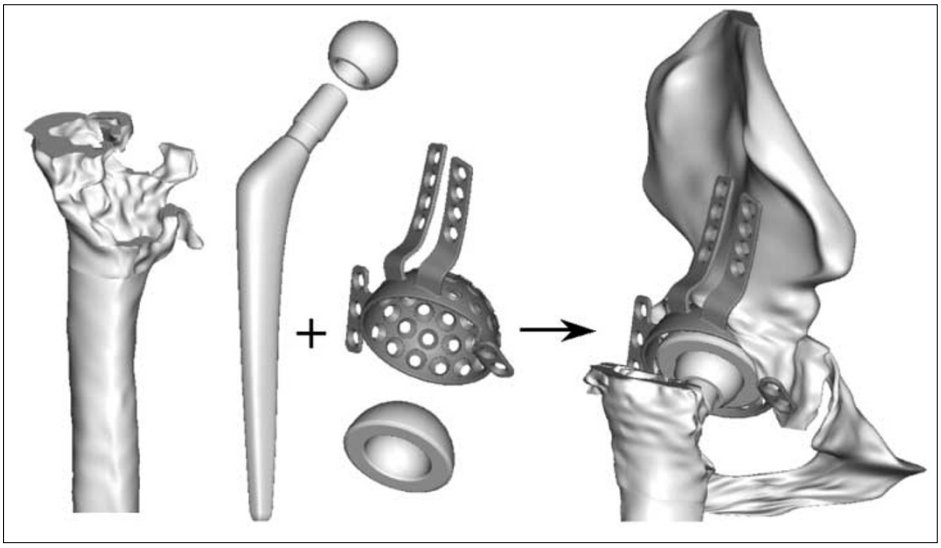

Fig. 4 Virtual simulation of the reconstructed joint

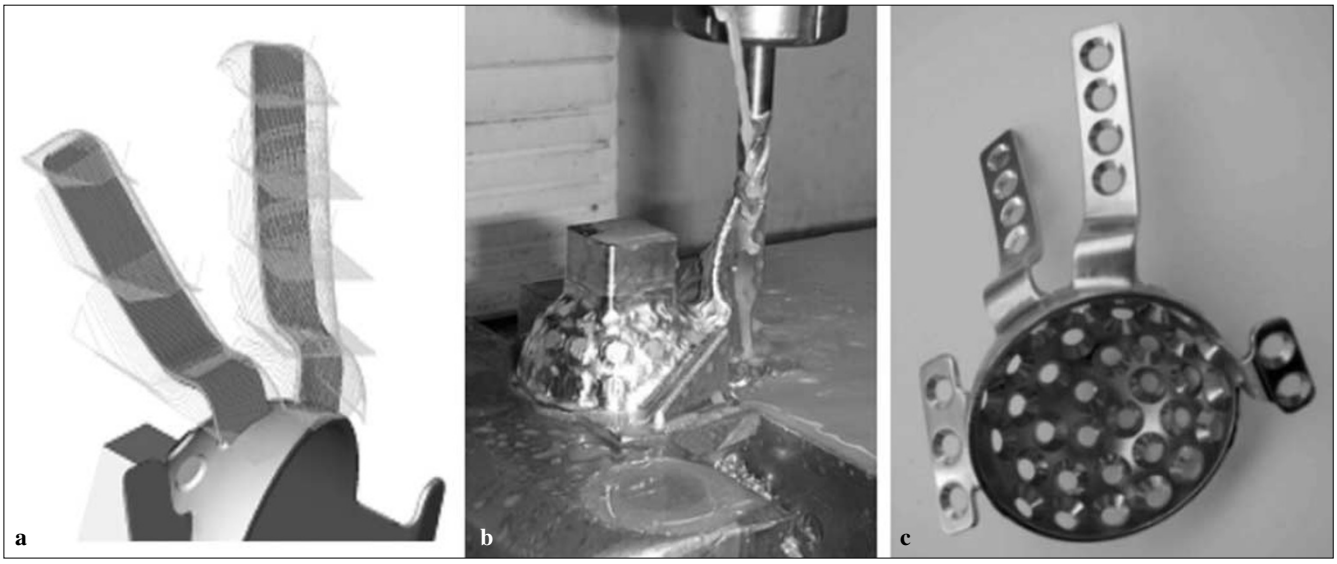

Fig. 5a-c *The stages of cage manufacture in the CAM system*. **a** Generated tool path. **b** Milling on CNC machine. **c** The manufactured cage

Surgical technique and preliminary assessment of the reconstructed acetabulum

We anticipated that, in the consecutive steps of the arthroplasty, after removing scar tissue from the acetabulum and the medullary canal of the femur, the following actions would be performed:

1. Refilling of the cleaned acetabulum with a layer of allogenic frozen bone grafts
2. Fixation of the cage into the pelvis by means of screws
3. Dense packing of the next bone graft layer in the fixed cage
4. Fixation of the polyethylene cup into the cage by means of cement
5. Implantation of the revision prosthesis stem into the femur.

The operation (approved by the Ethics Committee of the Military Institute of the Health Services, Warsaw, Poland) passed without great difficulty and according to plan. It should be emphasised that the shape of the cage strictly matched that of the patient's pelvis. Eight screws were used to fix the cage. The length of the limb was equalised. After two days, the patient began standing, and after 10 days she began walking with crutches. She left the hospital after 20 days in very good general condition. She was advised to walk with crutches and load the operated limb less than 20 kg. She was clinically observed every 6–12 weeks, at which time the range of joint motion was studied and radiographs were obtained (Fig. 6). After 8 months, as the patient suffered no pain in the operated joint, and given the absence of prosthesis migration and significant bone growth in the operated area, the patient was allowed to fully load the operated limb.

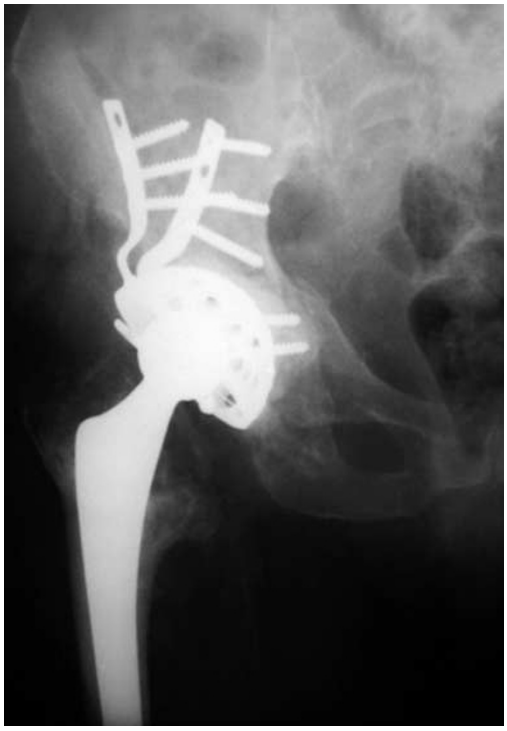

Fig. 6 Radiograph of the implanted joint

Presently the patient does not feel any ill-effects in the operated joint. Due to the necessity of hip joint arthroplasty on the other hip, she walks with one crutch, awaiting an operation.

Assessment of movement abilities and gait parameters of patient after the arthroplasty

One of the ways to verify the results of arthroplasty is to assess functionality of the joint after surgery. Various methods are applied to perform this assessment – from observation analysis of gait, through test performing, e.g. the Harris test, to gait analysis by means of advanced systems of gait parameters measurement. In the case of tests, the results depend mainly on the experience and subjective assessment of the person who supervises the test. Assessment performed by means of advanced systems of gait measurements yields more objective and precise results and comprises a greater range of studies. Measurements on such systems, apart from the direct possibility of assessing joint functionality, play an important role in assessing the clinical effects of arthroplasty. The human organism has an enormous capacity for adapting itself to external and internal stimuli, but adaptation mechanisms appear much earlier than clinical symptoms. Patient gait analysis after arthroplasty makes it possible to detect these clinical changes in advance.

Gait analysis of the patient in question was performed by means of a VICON 460 system (Vicon Peak, Oxford, UK) two days before the operation and 15 months afterwards. VICON is an automated system by means of which gait can be analysed in three-dimensional (3D) space using passive markers. For assessment of the revision arthroplasty, the differences between the results obtained before and after the operation are the most valuable. Comparing the two gait studies, the following aspects were observed:

- Increase of step length, on the average 3 cm in lll (from 0.33±0.056 m to 0.36±0.037 m) and 4 cm in rll (from 0.27±0.035 m to 0.31±0.029 m). The step length is lower than the normal step length by 67% in lll and 57% in rll. The other parameters did not change: gait velocity was 0.46±0.04 (41% of normal gait velocity for the same sex and age) and gait frequency was 85.7±2.17 steps/min (70% of norm).
- Symmetrical percentage fraction of the stance phase: asymmetry was eliminated. The percentage fraction of the stance phase measured before the operation was

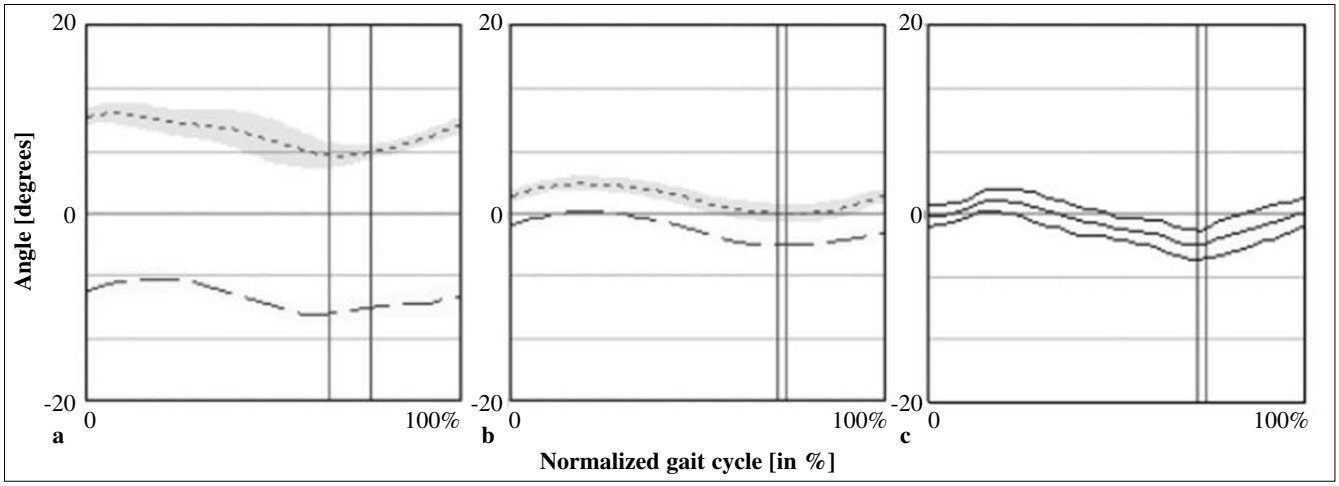

Fig. 7a-c *Pelvic rotation in transversal plane*. **a** Before the operation. **b** After the operation. **c** The norm. *Dashed line*, left side; *dotted line*; right side

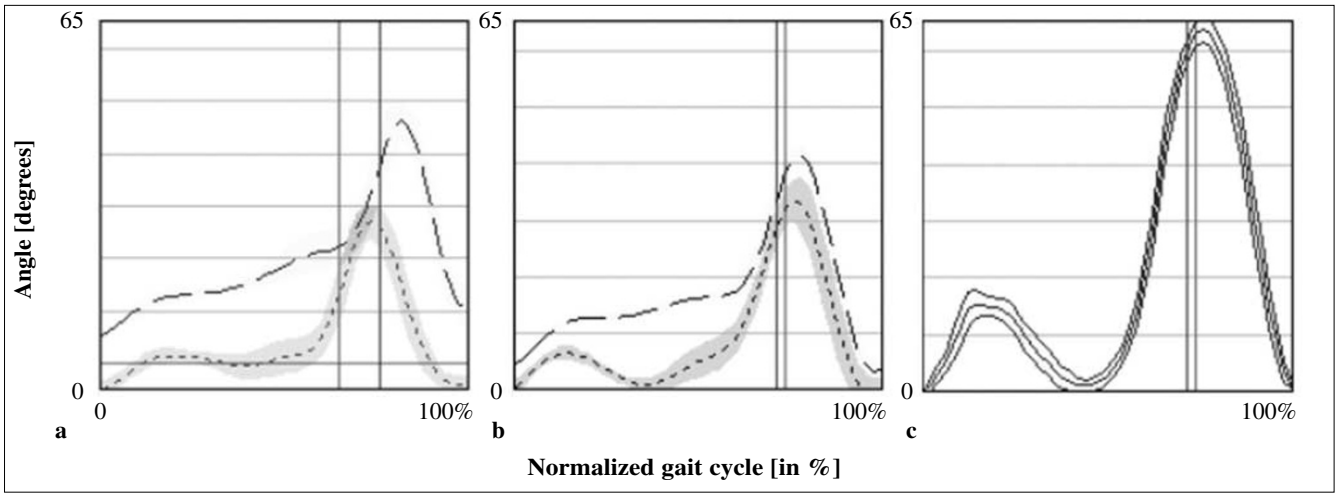

Fig. 8a-c *Knee joints in the sagittal plane*. **a** Before the operation. **b** After the operation. **c** The norm. *Dashed line*, left side; *dotted line*, right side

77.0%±0.029% in lll, 69.4%±2.45% in rll, and was greater than the norm by 17% in lll and 9% rll; asymmetry was equal to 8%. After the operation, the percentage fraction of stance phase was 73.2%±1.95% in lll and 72.1%±1.52% in rll (greater by about 12%) and asymmetry was eliminated.

- Decrease of pelvic rotation in the transversal plane from 12° to 2° (Fig. 7).
- Increase of range of motion in the hip joint in the sagittal plane from 44% to 53% of the right range.
- Proper positioning of the joints in the frontal plane (the previous adduction could have been caused by pelvic rotation in the transversal plane).
- Decrease in external rotation in the two joints.
- Appearance of the standard stance phase in the knee joint rll (Fig. 8).

Considering the age of the patient and the degree of joint deformation, it may be stated that the obtained results are satisfactory.

Conclusions

After reconstruction of the deformed joint and surgical implantation, the following remarks can be formulated:

1. Clinical observations show that the number of revision and “re-revision” arthoplasties is increasing (now it is approximately 20% of primary total hip replacements). This increases the need for custom-made prostheses. Development of computer techniques makes it easier to perform the design and manufacture of such prostheses.

2. In many complicated clinical cases, custom-made prostheses are the only solution for patients who have undergone such severe joint deformation that standard prostheses cannot be applied.
3. Computed tomography data effectively initiate the custom-made prosthesis design process. CT and CAD systems are useful in the reconstruction of a natural acetabulum.
4. The use of CNC machines to manufacture objects designed in CAD systems is effective.
5. The gait analysis system is a useful means of assessing the results of arthroplasty.

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