

# Personalized Hip and Knee Joint Replacement

Charles Rivière  
Pascal-André Vendittoli  
*Editors*



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Anastasia Belous, “**The Great Jump**”, oil on canvas, 2018, private collection

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Charles Rivière • Pascal-André Vendittoli  
Editors

# Personalized Hip and Knee Joint Replacement



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*To my many mentors, whose guidance and support have paved my professional journey, you have my sincere gratitude. And to my family, whose support and love have been endless. I would also like to thank and applaud the readers of this book. By doing so, you are demonstrating curiosity, creativity, audacity and an attention to detail not often seen. I consider these to be the key personality traits that can make a surgeon great, along with the realisation of what the term “excellence” means and how one can achieve it.*

*Charles Rivière*

*I wish to honour all the evolution enthusiasts that I have read, heard or met. Pioneering work requires going beyond one's horizons, experiencing uncertainty and assuming the risk of change. These people taught me to trust my ideas and not only those already established. I offer my sincere thanks to these innovative geniuses who inspire me every day and who make life a boundless experience. These people of great value, if they read these words, will recognise themselves surely, but their humility will make them doubt.*

*Pascal-André Vendittoli*

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## Foreword

It is a great pleasure for me to contribute to this book on the theme of "Personalized Hip and Knee Replacement". This vast subject is governed by the search for the most appropriate component and the subsequent implantation in a position that best fits the unique individual joint anatomy. This personalized approach for replacing joints cannot be limited, as it used to be, solely to the criteria of patient size and gender. The need for more precise procedures was obvious to me from the very beginning of my knee arthroplasty practice, most notably after I visited Leonard Marmor in Los Angeles in 1974. From 1972, Marmor used what he defined as the first "conservative total knee replacement". This involved the implantation of two condylar resurfacing components facing two tibial polyethylene plateaus, positioned from either side of the preserved tibial spine and cruciate ligaments. This type of implantation revealed a significant difference in the width of the two tibial plateaus for a third of patients, therefore resulting in asymmetrical prosthetic replacement. This anatomical peculiarity may explain the difficulty in adequately selecting the axial rotation of fixed-bearing total knee components, and the many clinical complications related to the failure to do so.

Other important criteria must also integrate the concept of specificity, in addition to the anatomical and technological considerations. It is essential to take patients' physiological age into account. The assertion that no patients under 60 years of age should receive a prosthesis is one that I have fought throughout my career, and still too often encounter. This should be considered obsolete. It must be replaced by the concept that at every age, a specific type of implantation exists, taking into account the general condition of the patient, their type of activity—especially professional—but also their level of sportsmanship. With regard to young patients, implants selected must be as bone and soft tissue conserving as possible. This will ease potential future revision surgery, making it almost comparable to a primary procedure. Hip resurfacing and partial knee replacements are good illustrations of this concept of conservative joint replacement. For fragile elderly subjects, the implantation should primarily aim to be safe by minimising the risks from surgery. Preventing risks of peri-prosthetic fracture and dislocation for hip replacement, and favouring unicompartmental knee replacement wherever possible, are therefore sound options. Between these ages, the choice of implants may vary.

A number of obstacles may be encountered when it comes to performing patient-specific joint replacement. Indeed, many hospitals have a rationalised

stock of implants, only offering surgeons a small range of implant designs. This is often due to economic factors, as determined by the administration, and, in some cases, may also be dictated by a head of department. He or she may favour more forgiving implants, such as posterior stabilised knee prostheses rather than more bone-preserving prosthetic replacements, and thus have an arbitrary implant of choice that all surgeons are encouraged to use. Finally, the increasing regulation of surgical practice in our modern society frequently sees young surgeons seeking reassurance through mastering the use of a single implant design, and therefore failing to acquire a personalized implant approach. The concept of patient-specific joint replacement will only be effectively applied and generalised after remedying these deterring factors.

The safety and efficacy of personalized implantation may be perceived as a challenge due to the multiplicity of implants used and techniques to master. Technology-assisted implantation will probably play a growing role in this area, potentially becoming the standard in the future. Operative planning in 3D, computer-assisted surgery, robotics and augmented reality may therefore be a key tool for the future and may soon confer additional legal protection for the surgeon. A lasting solution will have to be reached with regard to the economic restrictions. All considerations aside, we should remember that the most important factor in Personalized Hip and Knee Replacement is the acknowledgement and acceptance of an increasingly complex learning curve.

*Personalized Hip and Knee Joint Replacement* is a wonderful book that has been compiled expeditiously so as to be current and relevant. All chapters are written by international experts in the field, and these experts all have published experience with their topic. As such, the book focuses on evidence-based information. The book is very richly illustrated and, when appropriate, the details of the surgical procedure are effectively described. Congratulations to Charles Rivière and Pascal André Vendittoli who have accomplished this difficult task!

Philippe Cartier  
Neuilly-sur-seine, France

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## Preface

Hip and knee replacements are very successful procedures, despite the fact that they are affected by non-negligible rates of residual symptoms and complications. Unsatisfactory clinical outcomes are primarily explained by poor biomechanics of prosthetic joints. Interestingly, recent advances in both material and design of prosthetic components, as well as precise technologically assisted implantation, have not been game changers. This may be due to the fact that gold standard techniques for implanting hip and knee components aim to implant all patients similarly, thus neglecting the unique joint anatomy and kinematics of each individual. Systematic techniques for joint replacement were originally devised for simplifying implantation, making it more reliable in the surgeons' hands.

Since the initial worldwide spread of these systematic techniques in the 1970s (hip) and 1980s (knee), the world of arthroplasty has dramatically changed. Surgeons have become much more specialised, often fellowship-trained, with the aim of being an expert of a single joint (hip or knee) or type of procedure (joint replacement). Implant designs have become more sophisticated with modularity, various shapes and multiple sizes. Finally, precision and accuracy of implantation have significantly improved through the use of assistive technological tools (e.g. computed or robotic-assisted surgery, patient-specific cutting guides) and pre- or intra-operative tri-dimensional dynamic planning, respectively. These changes in practice over the last few decades, combined with recent evidence highlighting the detrimental clinical effect of neglecting individual joint anatomy and kinematics, have led to the development of a more personalized philosophy for arthroplasty.

The *Personalized Hip and Knee Joint Replacement* book has been written to set the path for the paradigm shift from a systematic to personalized surgery. It is a practical manual for the practicing or training orthopaedic surgeon, treating patients with hip and knee disorders, who intends to personalize the implantation of prosthetic components in order to achieve an optimal outcome for every patient. A description of personalized surgical techniques and component designs that aim to preserve the unique individual joint anatomy and kinematics, as well as the rationale behind these, is provided in detail. The technological tools that enable precise and accurate personalized implantations are also described.

We hope this book will pave the way to a significant philosophy change in orthopaedic practice and highlight the potentially deleterious clinical effects of homogeneous, simplistic surgical practices that are currently pushed by

some public or private organisations. With talent, expertise and technological support, there is no doubt that a “Personalized & À la Carte” philosophy for replacing joints will play a significant role in our future. We are most grateful to all the authors, who despite their already immense work commitments took on the task of writing a comprehensive, evidence-based and illustrated text with such quality. Their wisdom, expertise and dedication were simply outstanding. The quest for the forgotten joint is our ultimate goal.

Following the same path, we came to the decision to create an International Society named “Personalized Arthroplasty Society (PAS)” that would lead the paradigm shift from a systematic to personalized surgery (see the internet web site: [www.personalizedarthroplasty.com](http://www.personalizedarthroplasty.com))

The objectives of the Society are:

- To **improve the profile** of the “Personalized Arthroplasty” philosophy, through publications (research articles and textbooks) and educational events such as congresses and workshops.
- To foster **networking**, information sharing, mentoring, career opportunities, leadership training, and professional development in the field of “Personalized Arthroplasty”.
- To standardise the **teaching** of “Personalized Arthroplasty” through textbook, articles published in a trimestral special edition in an established peer-reviewed pubmed referenced journal, educational events (annual congress, workshops), and fellowship travel tour.
- To **support the assessment and refinement** of “Personalized Arthroplasty” (research and audit role): Support assessment projects on personalized arthroplasty. A collaboration with OTSR journal (5-years IF: 1.968) will be initiated with publication in special editions (PAS edition).

We are currently welcoming membership applications and are looking forward to build new strong scientific and friendship relations.

London, UK  
Montreal, QC, Canada

Charles Rivière  
Pascal-André Vendittoli



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# Contents

<b>1 Can Evidence-Based Medicine and Personalized Medicine Coexist? . . . . .</b>	<b>1</b>
Kim Madden and Mohit Bhandari	
<b>Part I Personalized Hip Arthroplasty</b>	
<b>2 Hip Anatomy and Biomechanics Relevant to Hip Replacement . . . . .</b>	<b>9</b>
Romain Galmiche, Henri Migaud, and Paul-E. Beaulé	
<b>3 Hip Replacement: Its Development and Future. . . . .</b>	<b>23</b>
Charles Rivière, Ciara Harman, Kartik Logishetty, and Catherine Van Der Straeten	
<b>Part II Performing Personalized Hip Replacement by Using Specific Implants</b>	
<b>4 Reproducing the Proximal Femur Anatomy Using Hip Resurfacing Implants . . . . .</b>	<b>35</b>
Julien Girard and Koen De Smet	
<b>5 Reproducing the Proximal Femur Anatomy Using Neck Anchorage Stem Design . . . . .</b>	<b>45</b>
Philippe Piriou and James Sullivan	
<b>6 Reproducing Proximal Femur Anatomy with Custom Stems. . . . .</b>	<b>53</b>
Elhadi Sariali, Alexandre Mouttet, Xavier Flecher, and Jean Noel Argenson	
<b>7 Reproducing the Proximal Femoral Anatomy: Large-Diameter Head THA . . . . .</b>	<b>65</b>
William G. Blakeney, Jean-Alain Epinette, and Pascal-André Vendittoli	
<b>8 Reproducing the Proximal Femur Anatomy: Modular Femoral Component . . . . .</b>	<b>75</b>
Aldo Toni, Francesco Castagnini, and Susanna Stea	

### **Part III Performing Personalized Hip Replacement by Using Technological Tools to Achieve Implants Position**

- 9 Reproducing the Proximal Femur Anatomy: 3D Preoperative Planning and Custom Cutting Guides** ..... 87  
Tyler A. Luthringer and Jonathan M. Vigdorichik
- 10 Reproducing the Hip Anatomy: Intraoperative Planning and Assistive Devices (CAS, Robotics)** ..... 99  
Marius Dettmer, Stefan W. Kreuzer, and Stefany Malanka

### **Part IV Personalizing the Acetabular Component Position**

- 11 Kinematic Alignment Technique for Total Hip Arthroplasty** ... 113  
Charles Rivière, Ciara Harman, Oliver Boughton, and Justin Cobb
- 12 The Effect of Spinopelvic Motion on Implant Positioning and Hip Stability Using the Functional Safe Zone of THR** ..... 133  
Nathanael Heckmann, Nicholas A. Trasolini, Michael Stefl, and Lawrence Dorr
- 13 Modern Imaging in Planning a Personalized Hip Replacement and Evaluating the Spino-pelvic Relationship in Prosthetic Instability** ..... 143  
Omar A. Behery, Lazaros Poultsides, and Jonathan M. Vigdorichik

### **Part V Personalized Knee Arthroplasty**

- 14 Knee Anatomy and Biomechanics and its Relevance to Knee Replacement** ..... 159  
Vera Pinskerova and Pavel Vavrik
- 15 The Future of TKA** ..... 169  
William G. Blakeney and Pascal-André Vendittoli
- 16 The Kinematic Alignment Technique for Total Knee Arthroplasty** ..... 175  
Charles Rivière, Ciara Harman, Oliver Boughton, and Justin Cobb
- 17 Restricted Kinematic Alignment: The Ideal Compromise?** .... 197  
William G. Blakeney and Pascal-André Vendittoli
- 18 Unicompartmental Knee Arthroplasty** ..... 207  
Justin Cobb and Charles Rivière

**Part VI Performing Personalized Knee Replacement Using Specific Implants**

**19 Custom Unicompartmental Knee Arthroplasty** . . . . . 221  
 Etienne L. Belzile, Michèle Angers, and Martin Bédard

**20 Patello-femoral Replacement** . . . . . 233  
 Romagnoli Sergio, Petrillo Stefano, and Marullo Matteo

**21 Combined Partial Knee Arthroplasty** . . . . . 243  
 Amy Garner and Justin Cobb

**22 Custom Total Knee Arthroplasty** . . . . . 255  
 Elliot Sappey-Marinier, Carsten Tibesku, Tarik Ait Si Selmi,  
 and Michel Bonnin

**23 Bicurciate Total Knee Replacement** . . . . . 265  
 James W. Pritchett

**Part VII Performing Personalized Knee Replacement by Using Specific Tools to Achieve Implants Position**

**24 Kinematically Aligned Total Knee Arthroplasty Using Calipered Measurements, Manual Instruments, and Verification Checks** . . . . . 279  
 Alexander J. Nedopil, Stephen M. Howell, and Maury L. Hull

**25 Kinematic Alignment Total Knee Replacement with Personalized Instruments** . . . . . 301  
 William G. Blakeney and Pascal-André Vendittoli

**26 Performing Patient-Specific Knee Replacement with Intra-Operative Planning and Assistive Device (CAS, Robotics)** . . . . . 311  
 M. Cieviet-Bonfils, C. Batailler, T. Lording, E. Servien,  
 and S. Lustig

**27 Augmented Reality Technology for Joint Replacement** . . . . . 321  
 Edouard Auvinet, Cedric Maillot, and Chukwudi Uzoho

**28 Assessing the Quality of Knee Component Position Following Kinematically Aligned Total Knee Arthroplasty** . . . . 329  
 Raj R. Thakrar and Sam Oussedik

**29 ‘À La Carte’ Joint Replacement** . . . . . 343  
 Charles Rivière, Ciara Harman, and Kartik Logishetty

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## About the Editors



**Charles Rivière** is a French Joint Reconstruction Surgeon and Clinical Researcher in orthopaedic surgery at Imperial College London (MSK Lab), the South West London Elective Orthopaedic Centre, and the Centre De l'Arthrose—Clinique Du Sport (Bordeaux Mérignac, France). His principal research activities are focussed on the development and evaluation of personalized techniques for implanting hip and knee prostheses, namely kinematic alignment. On completion of his training in orthopaedic surgery in Bordeaux, he undertook 3 years of specialist training in

hip and knee reconstruction in Paris (Pr. T. Judet), in London (Mrs. Sarah Muirhead-Allwood), and in Montreal (Pr. P.A. Vendittoli). Another of his mentors is Justin Cobb, whose expertise in conservative techniques for joint replacement significantly influenced Charles' surgical philosophy. In 2015, he was awarded a PhD from Aix-Marseille University. Currently, he holds a position of Honorary Senior Clinical Lecturer in orthopaedics at Imperial College London. His studies are largely published and presented in peer-reviewed journals and international congresses.



**Pascal-André Vendittoli, MD, MSc, FRCS(C)** is Professor of surgery and Clinical Researcher in orthopedic surgery at Maisonneuve-Rosemont Hospital/University of Montreal. His principal research activities are the evaluation of new surgical techniques, new technologies, and new orthopaedic implants, mainly in the framework of prospective and randomised trials. After his training in orthopaedic surgery, he undertook specialist training in hip and knee reconstruction in Melbourne, Australia, and in knee joint replacement with Paolo

Aglietti in Florence, Italy. In 2005, he obtained a Master of Biomedical Sciences/Clinical Research from Montreal University.

Dr. Vendittoli was elected as Research Director of the Orthopaedics Division of Montreal University. In recent years, Dr. Vendittoli's work was presented more than 300 times at peer-reviewed congresses, and he was invited on more than 200 occasions as speaker. He has published more than 125 scientific articles on hip and knee arthroplasty in peer-reviewed journals. As a Professor of Surgery, he supervised multiple students (Master, Doctoral, and Postdoctoral) and arthroplasty fellows. He is the Program Director of the postdoctoral program in hip and knee reconstruction at Montreal University.

In 2003, he received the Alexandra-Kirkley Award for the best research by a young investigator by the Canadian Orthopaedics Association. In recognition of his research activities, since 2007, he is awarded the title of Clinical Researcher from the Fonds de la Recherche en santé du Québec. In 2009, he won the "John Charnley award" from the American Hip Society. In 2010, he received the Founders' medal for best basic science research work by the Canadian Orthopedic Association. In 2016, he received the "Edward Samson award", the most prestigious recognition from the Canadian Orthopedic Association.



# Can Evidence-Based Medicine and Personalized Medicine Coexist?

1

Kim Madden and Mohit Bhandari

## 1.1 What Is Evidence-Based Medicine?

Evidence-based medicine (EBM) is a philosophy of healthcare that aims to ensure that healthcare interventions are applied based on the best available evidence, combined with clinical expertise and patient values [1]. This is in contrast to the philosophy of “eminence-based” medicine, which is characterized by a paternalistic view that expert clinicians know what is best for their patients by virtue of their clinical experience. The term EBM was coined by Professor Gordon Guyatt in 1990 and further developed by academic physicians such as Professor David Sackett. Sackett described EBM as having three integrated key components: best available evidence, clinical expertise, and patient values [1]. Here, we discuss each of these three components in more detail.

### 1.1.1 Best Available Evidence

It makes intuitive sense that healthcare professionals should be reasonably sure that a treatment works and that the benefits outweigh the

harms before wide implementation of the intervention. It is important to question unsubstantiated claims about treatments, diagnostic tools, and other aspects of healthcare so that we do not widely use treatments that are ineffective or do more harm than good. Using systematic and scientific methodology, EBM gives us the tools to evaluate healthcare interventions and determine how strong and convincing the evidence is for those interventions, and therefore whether we should believe claims of their efficacy. The phrase “best available evidence” implies that some evidence is better than other evidence. This brings us to one of the key principles of EBM: the hierarchy of evidence. Many healthcare professionals are aware of the “evidence pyramid” that places high-quality evidence on the top of the pyramid and low-quality evidence on the bottom of the pyramid [2]. EBM helps us to sort out which studies are high quality and which studies are low quality. However, this categorization is not binary; quality of evidence is a continuum. In general, the highest quality of evidence for questions about treatment efficacy comes from randomized controlled trials (RCTs) and systematic reviews of RCTs. The reason for this is that, when done correctly, the process of randomization should balance the known and unknown prognostic factors across treatment groups, with the only difference between groups being the treatment of interest. RCTs are not always at the top of the hierarchy of evidence. EBM also

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encourages downgrading evidence in the presence of substantial methodological flaws [3]. For example, if a study is too small to properly balance prognostic factors across groups, that could lead to the study being downgraded from the top level of evidence. Prospective cohort studies are often at the second tier of evidence (Level II evidence) because they lack the randomization process that aims to balance prognostic factors. They are therefore more biased and of lower quality. Retrospective studies are Level III evidence because they are subject to even more bias than prospective studies, for example, recall bias. Case series are Level IV evidence because they lack a control group. We therefore cannot be sure whether apparent treatment effects can actually be attributed to the treatment or some other effect such as time. Expert opinion is Level V evidence because opinions can easily be biased by personal views, conflicts of interest, and other factors such as confirmation bias. By applying a critical lens to studies, we can practice “enlightened scepticism” to be reasonably sure that the treatments that we choose to use are effective.

### 1.1.2 Clinical Expertise

Critics of EBM often protest that EBM downplays the role of the clinician’s expertise in favor of a cold, calculating style of medicine based only on evidence [4]. This is not the case. Evidence is not a substitute for clinical training and experience. Evidence alone is never enough to make a clinical decision. The proper application of EBM requires the integration of expertise and evidence. The JAMA series on the Users Guides to the Medical Literature, a key EBM resource, gives guidance on how to evaluate whether particular evidence is applicable to specific patients [5]. It teaches clinicians to ask “Were the study patients similar to the patient in my practice?” To answer this question, clinicians must use their diagnostic expertise and judgment. For example, surgeons may decide that a study that included mostly elderly female patients with comorbidities would not necessarily apply to an elite male athlete, even if the evidence is of very high quality.

### 1.1.3 Patient Values

The third major component of EBM is the integration of patient values [6, 7]. Although this point is the most often forgotten, it has been written into formal definitions of EBM since the 1990s [1]. Along with the best available evidence and the clinician’s expertise, we must take into account the patient’s preferences. For example, an active, newly retired man with hip osteoarthritis may place more value on implant longevity than a very elderly man. Similarly, a young tradeswoman with moderate knee arthritis may value whichever treatment option can get her back to work faster. This principle particularly emphasizes that EBM is not a set of rigid rules, nor is it a one-size-fits-all approach to treating patients.

---

## 1.2 Are There any Drawbacks to EBM?

EBM is not perfect and is ever-evolving. A major practical challenge is that performing EBM properly requires a lot of practice and skill. However, this is the same for any other skill, for example, arthroplasty surgeons train for a decade or more to become experts at joint replacement. Sometimes, feasibility issues arise in EBM, for example, to get the highest quality evidence (i.e., RCTs), it can take years and cost millions of dollars to do it correctly. However, there are quicker and cheaper designs that can be done if an RCT is not feasible. For example, one could conduct retrospective chart reviews with matched controls or statistical adjustments based on propensity scores. This design is not as strong as an RCT but can efficiently provide better evidence than anecdote alone. One of the biggest challenges of EBM is that sometimes policymakers and clinicians forget that evidence alone is not sufficient, and they create overly strict policies that they say are evidence based. There needs to be integration of clinical judgment and patient values, which is in harmony with the principles of personalized medicine. Another perceived drawback of EBM is the misconception that results from trials can never apply to individual patients; they only

apply to the “average patient.” However, EBM books [5] and workshops [8] give explicit guidance on how to apply EBM to individual patients.

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### 1.3 What Is Personalized Medicine?

Personalized medicine is a philosophy of treatment that arose from genomics, with particular applications in cancer treatment. The idea is that patients can be stratified into risk groups (e.g., biomarker present vs. absent) and provided with personalized treatment based on that risk factor [9]. This philosophy has clear applications in orthopedics, particularly in arthroplasty where many patients are not satisfied with their replaced joint despite a lack of major complications [10]. Kinematic alignment techniques that restore individual joint anatomy and soft-tissue balance, custom implants that can more accurately mimic the natural joint, robotic surgery for more precise cuts, and 3D printing are all innovations that can benefit the field of orthopedics by individualizing particular aspects of patient care. This intuitively sounds like a good idea. However, custom implants and technological innovations can drive up costs of surgery. We need evidence that these interventions are worth the additional money.

---

### 1.4 Are EBM and Personalized Medicine at Odds?

When Professor Gordon Guyatt was asked this question, he responded with “we find this somewhat amusing” [11]. The idea that personalized medicine is the opposite of EBM, or that they are somehow at odds, stems from a fundamental misunderstanding of what EBM is and is not. Particularly, the misconceptions that EBM is dogmatic, do not take into account patient values or differences between patients, there is no room for clinical judgment, that only randomized trials matter, and that EBM is a static set of rules, are misconceptions that contribute to the divide between personalized medicine and EBM. Let us address these misconceptions.

- *EBM is dogmatic.* EBM is not dogma; it is a set of guidelines that helps us decide whether a healthcare intervention is effective and safe and whether the evidence applies to our patients. Individual expertise, decision making, and judgment come into play at every stage of EBM.
- *EBM does not take into account patient values.* One of the three basic principles of EBM is that patient values and differences between patients should be taken into account when choosing a treatment. There is a whole field dedicated to how this can best be achieved, for example, with the use of patient decision aids and shared decision making [12]. Additionally, EBM is beginning to involve patients as collaborators when designing research and selecting outcomes for studies [13].
- *EBM does not take into account differences between patients.* EBM gives guidance on subgroup analyses to take into account differences between patients [14]. Subgroups allow us to draw different conclusions for different groups of patients by categorizing them by a prognostic variable of interest, just like “stratified medicine.” For example, in the SRINT trial investigating reamed versus unreamed intramedullary nailing for tibia fractures, the treatment effects varied for patients with open fractures versus closed fractures [15].
- *There is no room for clinical judgment.* One of the three basic principles of EBM is that clinical judgment cannot be replaced by evidence alone. Clinical expertise is still required to decide whether the evidence can be applied to a specific patient.
- *Only randomized trials matter.* EBM acknowledges that there are many ways to obtain evidence. The existence of the hierarchy of evidence proves this. Sometimes, patients cannot be randomized for ethical or feasibility reasons. In this case, EBM would say that an RCT is not the best available evidence. EBM has also always had an option for an N-of-1 trial, which is a trial where a single patient is their own control group [16]. This N-of-1 approach allows clinicians to determine whether a treatment works for that specific

patient and provides better evidence than anecdote alone.

- *EBM is a static set of rules.* EBM is not a set of rules (see point 1), and EBM is constantly evolving. Some of the newer innovations in EBM include better methods of disseminating evidence (e.g., OrthoEvidence; [myortho-evidence.com](http://myortho-evidence.com)), extending EBM concepts to diagnostic and prognostic studies as well as interventions (e.g., the work of the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) group) [17], methods of synthesizing information quickly (e.g., BMJ Rapid Recommendations; [bmj.com/rapid-recommendations](http://bmj.com/rapid-recommendations)), and ever-evolving methods of analyzing data, particularly non-RCT data.

## 1.5 So, Can EBM and Personalized Medicine Coexist?

Not only *can* EBM and personalized medicine coexist, they *should* coexist. Personalized medicine-based interventions contribute to the growing number of innovations in orthopedics and other fields. However, these interventions still need to be evaluated for effectiveness, cost-effectiveness, and safety before they are widely adopted, just as standard approaches need to be evaluated with a critical lens. For example, one could randomize patients to receive conventional unicompartmental knee arthroplasty (UKA) versus custom UKA. Such a study would combine the best of both worlds and promote innovation in our field. There is no reason that the philosophies of EBM and personalized medicine cannot work together.

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**Part I**

**Personalized Hip Arthroplasty**



# Hip Anatomy and Biomechanics Relevant to Hip Replacement

# 2

Romain Galmiche, Henri Migaud,  
and Paul-E. Beaulé

## Key Points

- Surgeons have to cope with many variations in anatomy depending on gender, geographic area, or specific diseases.
- Surgeons have to either adapt their surgical technique and/or implant positioning to deal with all anatomies or use custom-made implants.
- Implant positioning needs to be accurate as error(s) in the position of component(s) can modify essential biomechanical parameters and thus jeopardize the clinical result.
- A better understanding of the dynamic/functional orientation of articular anatomical structures and the femoro-acetabular prosthetic interplay will benefit hip arthroplasty and feed future innovations.

Modern total hip replacement and hip resurfacing have been shown to generate good long-term clinical outcomes. Advances in materials, engineering, and improved knowledge in joint anatomy and biomechanics, have enabled this success. Successful hip prosthetic surgery relies on a proper understanding of the hip anatomy and its biomechanics. In this chapter, we will review these essential points.

## 2.1 Normal Hip Biomechanics

Understanding of the human gait has progressed since the early methods of chronophotography by Etienne-Jules Marey, which enabled capture of human movement. Expansion on this through advancement in technology, such as infrared cameras, electromyographs, and force platforms, has led to a greater understanding not only of human locomotion, but also the effects our surgery has. The importance of hip biomechanics has become more and more prominent with the development of gait laboratories giving us a more accurate, but also more complex, view of the hip's in vivo function.

### 2.1.1 Kinematics

Hip motion is allowed in three planes (sagittal, frontal, and transverse) due to its **ball-and-socket**

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**configuration.** Nevertheless, some authors have described the femoral head with a conchoid (or ellipsoid) shape [1]. This particular shape makes the joint less likely to sublux when compared to a true ball-and-socket joint. Moreover, this shape may contribute to generation of the optimal stress magnitude and distribution [2]. In the same manner, the horseshoe geometry of the acetabular cartilage has been shown to optimize the contact stress distribution. Thus, through the acknowledgment of these anatomic features, we immediately understand that allowing mobility while maintaining stability is the first challenge a prosthetic spherical implant faces.

The sagittal plane portrays the greatest **passive range of motion**: flexion, on average, can reach  $100^\circ$  (extended knee) and  $140^\circ$  (flexed knee, due to the hamstring release). Extension is  $15^\circ$ – $20^\circ$ . In the frontal plane, the range of abduction is from  $10^\circ$  to  $45^\circ$ , whereas the range of adduction is  $10^\circ$ – $30^\circ$ . The external rotation reaches  $60^\circ$  and the internal rotation  $30^\circ$ , but it can go further when the hip joint is flexed due to the release of the soft tissues (up to  $90^\circ$  for external and  $60^\circ$  for internal rotation). However, these figures are subject to interindividual variation. Gender, age, individual patient anatomy (femoral neck angle, femoral neck offset, acetabulum version ...), and level of physical activity are features that can alter the hip range of motion. For example, a subject with a coxa valga tends to exhibit a better abduction peak angle than a coxa vara subject, due to the delayed impingement between the femoral neck and the acetabular labrum.

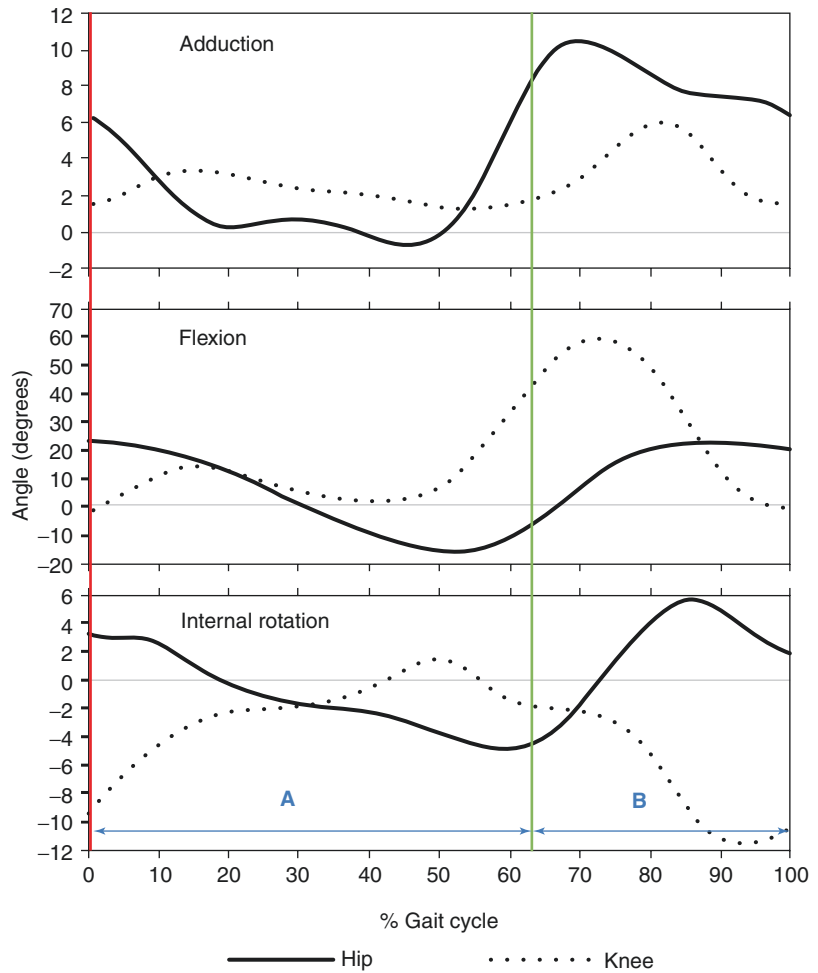
As an orthopedic surgeon, it is important to know the **values of hip motion involved in activities of daily living**. For example, tying shoe laces with feet on the floor will require up to  $125^\circ$  hip flexion,  $19^\circ$  external rotation, and  $15^\circ$  of abduction; ascending stairs will require a mean hip flexion of  $70^\circ$ , whereas descending them needs  $35^\circ$ . **Gait** is characteristic of the human species. This is a succession of imbalance phases that is actually much more complex than the human eye can see. Measurements in the sagittal plane (Fig. 2.1) show that the hip joint is maximally flexed ( $35^\circ$ – $45^\circ$ ) during the late swing

phase of gait, as the limb moves forward for heel strike. Then, the hip extends as the body moves forward, and the extension peak is reached at heel-off. The frontal and transverse planes are also involved. Abduction occurs during the swing phase of gait and reaches a maximum just after toe-off. At heel strike, the hip joint reverses into adduction and keeps it during the entire stance phase. The hip joint is externally rotated during the swing phase and, to provide a fitted angle for the foot strike, the hip rotates internally. This internal rotation is gradually lost as the contralateral hip moves forward. One should also consider the motion of the pelvis (in sagittal, axial, and frontal planes) during the walking sequence. Pelvic motion is highly variable between individuals and its amplitude depends on multiple parameters, such as walking speed, pelvic and hip anatomy (e.g., width of pelvis), flexibility of the spine and the hips, etc. This pelvic motion probably has a significant influence on the hip biomechanics and the risk of degeneration. One must acknowledge that the pelvis undergoes axial rotation (about  $8^\circ$ ) as the leg moves forward. There is a heightening of the hemi-pelvis before toe-off as well (corresponding to a  $5^\circ$  rotation in the frontal plane), introducing the concept of “pelvic vertebra” asserted by Jean Dubouset. These motions require further investigation, given they are highly variable between individuals and may produce deleterious effects on bearing components (edge loading, impingement) in dynamic situations [3].

### 2.1.2 Kinetics

Joint reaction forces are the forces generated within the joint in reaction to forces acting on the joint. For the hip, it is the result of the need to balance the moment arms of the body weight and abductor tension in order to keep a leveled pelvis. The hip contact forces are then a combination of ground reaction force to body weight, and of internal muscle contraction forces. The resultant hip reaction forces can be calculated either *in vivo*, by strained-gauged prosthesis, or by analytical approaches (2D models or more sophisticated 3D

**Fig. 2.1** Hip’s movements in the three dimensions during a normal gait cycle. Red vertical line represents heel-strike and green vertical line is toe-off. *A* Stance phase, *B* Swing phase



models). In a simple 2D model, when both legs support the weight of the body equally, in a standing position, the weight force vector is centered between the two hips. As a result, each femoral head supports one-half of the body weight. Indeed, in this model the pelvis is stable and there is no muscle reaction force to add in. During a single-legged stance, five-sixths of the body weight act on the femoral head in charge; its vector is vertical. In parallel, the abductor muscle force is oriented medially and superiorly at an assumed 30° angle from the vertical line. The lever arm of both body weight and abductor muscles can be determined on an AP pelvis radiograph (Fig. 2.2). Thus, the abductor muscles’ force multiplied by their lever arm (external moment) has to be equal to the bodyweight force multiplied by its lever arm

(internal moment), in order to keep a poised pelvis. Since the effective lever arm of abductor muscles is considerably shorter than the effective lever arm of body weight, the combined force of abductors must be a multiple of body weight. It ensues peak hip joint forces can reach 1.8 to 4.3 times body weight during gait [4]. These numbers could rise to eight times body weight for activities like running or skiing. This highlights how these forces will play a first rank role in the selection of components, implantation, wear, and durability. On the femoral head, maximum contact pressures occur at the supero-anterior area during walking, whereas for the acetabulum, the supero-posterior zone is more exposed to constrain. When moving from standing to sitting position or from sitting to standing position, the contact pressure is higher

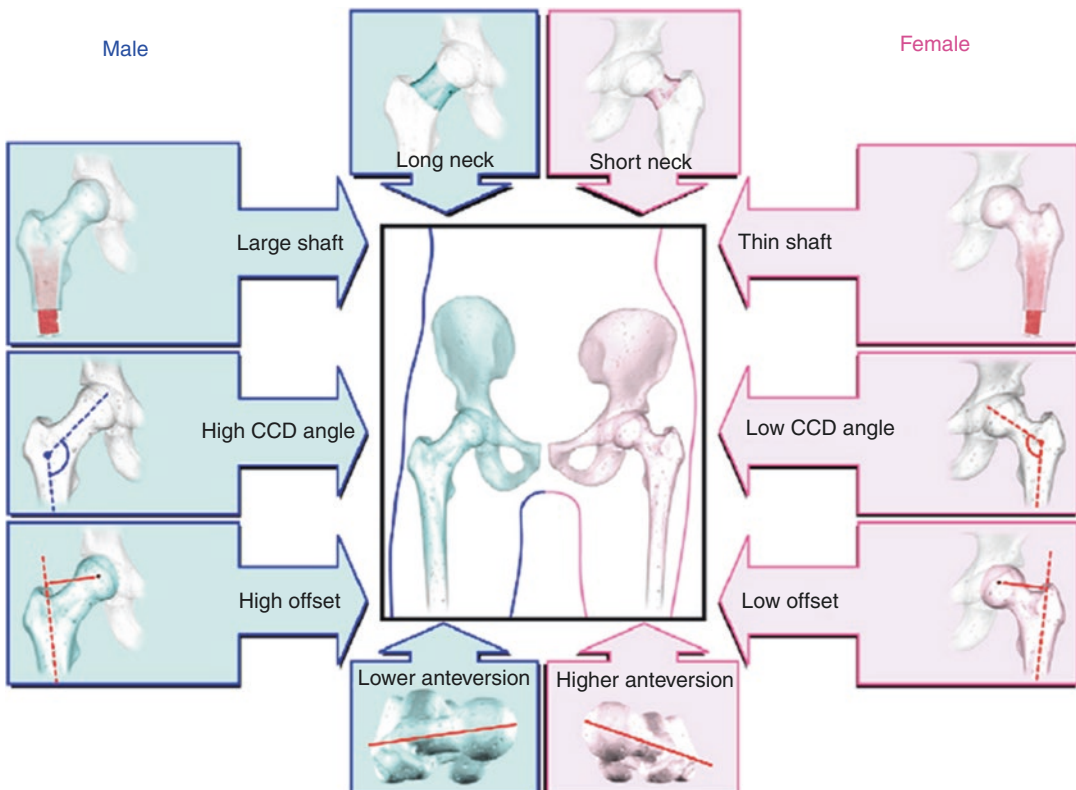


when the contact patch between the head and cup extends over the cup rim, which results in a large increase in local pressure, disruption of the lubrication mechanism, and increased wear. Clearance is now known to be an important factor in edge loading phenomenon [7]. This consideration is of high importance specifically for large diameter MoM bearings. A cup abduction angle of  $45^\circ$  or less is recommended to avoid excessive wear. It is of particular importance for MoM resurfacing in order to avoid edge-loading phenomenon. The effect of cup anteversion on wear is less straightforward and should be considered alongside the femoral version [8]. Nevertheless, modifying the cup inclination and/or anteversion will influence both the anterosuperior and the posteroinferior cup-head contact areas in opposite ways. For hard on smooth bearing couples, liner wear rates for 22, 28 or 32 mm heads do not vary significantly. Nevertheless, volumetric wear increases with head size, as it impacts the sliding distance between bearing components.

## 2.2 Variability in Hip Anatomy

In order to restore physiological hip biomechanics, THR surgery often aims to respect the patient's individual anatomy. However, hip anatomy is subject to a high interindividual variability. Immediately we understand the surgical difficulties related to this, in particular our capacity to restore the infinite natural variation with prosthetic implants.

**Are there gender differences?** In addition to the age, weight, and height, which play a major role in interindividual differences, there are other elements linked to anatomical variation. Gender is the first parameter associated with anatomical variability [9–13], with the pelvis exhibiting specific characteristics depending on gender; in females the pelvis is wider and the acetabulum generally deeper with greater anteversion when compared to males:  $18^\circ$  vs.  $21^\circ$  [14] and inclination  $38.5^\circ$  vs.  $36^\circ$  [15] (Fig. 2.3). These differences are partially explained by the developmental



**Fig. 2.3** Main gender differences regarding hip morphology [14]

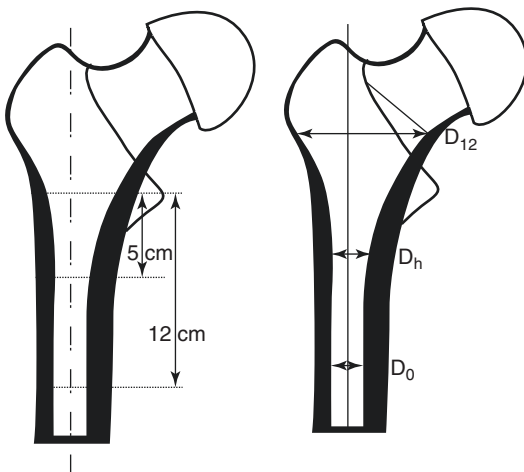
response to the need to give birth, where the birth canal is wider. However, with the broader pelvis, the body-weight lever arm is increased, which is associated with a deeper acetabulum (up to *coxa profunda*), thus reducing the body-weight lever arm. On the femoral side, females have a smaller femoral head diameter (adjusted for height and weight), a greater femoral anteversion, thinner femoral shaft, and a lower femoral shaft-neck angle with an associated smaller femoral offset when compared to men: 48 mm vs. 55 mm. Another key difference is the lower bone mineral density seen in females, especially after menopause, increasing the risk of peri-prosthetic fracture. These anatomical differences and their impact on joint replacement were quite evident with metal-on-metal hip resurfacing, where the smaller head size and acetabular orientation lead to a higher risk of failure. Differences are also found in the range of motion: women exhibit a greater peak hip flexion and internal rotation (hip at 90° flexion), whereas men show greater peak hip extension and external rotation.

**Are there racial/ethnic variants?** A number of studies, mainly from the 1950s, reported wider pelvises (both pelvic inlet and outlet) in the Caucasian population compared to the African population. This was thought to be associated with a higher geographic latitude. Many factors can explain these differences in pelvic shape around the world. The climate adaptation theory, which claims that narrower pelvises are seen in lower latitudes, while wider pelvises are seen in more northern areas in order to save heat and energy, has recently gained attention [16]. It questions the original, and until now, widely accepted theory that pelvic shape is the result of the evolutionary compromise (obstetric dilemma) between efficient bipedal locomotion and the safe parturition of a neonate. In reality, it is probable that multiple factors influence pelvic shape, and that environment and lifestyle (e.g., alimentation, activities) are likely to be equally as responsible as ethnic/geographic factors. For example, with regard to the neck-shaft angle, the activity level is a strong determinant, given that

the neck tends to become more varus as the activity level increases [9, 10]. Finally, racial differences in sacral geometry and spino-pelvic alignment have already been reported [17] in addition to gender differences [18].

**Is there a “normal” hip?** Independent of gender or ethnic origin, some constitutional variations are found among us, and they sometimes lead to a pathological process. Acetabular retroversion on plain X-ray can affect 6% of hips in a healthy population and up to 20% and 42% in osteoarthritis and Legg–Perthes–Calve cohorts, respectively [19, 20]. *Coxa profunda* may affect 5–20% of the whole population [21]. Acetabular retroversion represents a particular form of hip dysplasia, characterized by abnormal posterolateral orientation of the acetabulum. This pathophysiology predisposes the individual to subsequent anterior impingement of the femoral neck upon the anterior acetabular margin and fibrous labrum. Similarly, developmental hip dysplasia has a prevalence of 3.6–4.3% in the healthy adult population [22]. These pathologies can present a technical challenge for prosthetic surgery, particularly in their extreme states, which may involve a combination of hip dislocation, leg length discrepancy, posterior–superior acetabulum defect, and acetabulum retroversion. Dynamic study of the pelvis–femur relationship can complicate the notion of anteversion and retroversion. Firstly, pelvic tilt values in the standing position differ from one individual to another, with an average of 12° in the Caucasian population with standard deviation around 6° [17]. In addition, the pelvic tilt varies between supine, standing, and sitting positions, thus modifying the functional orientation of the acetabulum; this is enabled by the lumbar spine sagittal flexibility [23–25]. Thus, one has to know that these variations cannot be ignored, especially for cup positioning: in the supine position, the pelvis tilts anteriorly, which decreases anteversion of the acetabular component, while in the standing and sitting positions, the reverse happens and anteversion is increased [24, 26]. With regard to the femoral neck-shaft angle, Boese et al. reported in

a review article that the interindividual differences in the healthy population can range from 98° to 160° and from 115° to 155° in the osteoarthritic population [27]. This in turn affects the femoral offset, which is directly linked to the neck-shaft angle and femoral neck length. Similarly, femoral torsion can also vary, resulting in anteversion or retroversion of >40°; this may justify the need for 3D templating given regular AP pelvis radiographs are less accurate in assessing femoral torsion and medial offset. In addition to these key reconstruction parameters, the endofemoral canal can take the form of several different shapes, as measured by the femoral flare index and the cortico-medullary index (Fig. 2.4) [28]. This is of particular relevance in cementless fixation, where the need for a close bone–prosthesis interface is essential. One may favor hip resurfacing in some of these more complex situations (Fig. 2.5). In addition, anatomical variations exist in the vascularization of the femoral head, particularly the role of the inferior gluteal and medial femoral circumflex arteries, which are important to consider in hip resurfacing arthroplasty [29]. Each hip is therefore defined by an infinite combination of anatomical and geometric parameters, in addition to its functional capacity.



**Fig. 2.4** Femoral Flare Index =  $D_0/D_{12}$ ; Cortico-medullary Index =  $(\text{Medial} + \text{Lateral cortical thickness})/D_0$



**Fig. 2.5** Example of a 50-year-old woman who portrays an extra-small Femoral Flare Index. As, restoration of the femoral offset would have been difficult with a regular femoral stem, resurfacing provides a predictable anatomical reconstruction

## 2.3 Anatomy Modifications Affecting Clinical Results

### 2.3.1 Relative to Components' Positioning

Hip replacement and resurfacing aim to achieve sustainable restoration of hip mobility without pain. Component positioning plays a role in every aspect of the clinical outcomes: function, wear rate, occurrence of complication, and components' life span.

**Center of rotation.** In the frontal plan, the acetabular offset defines the mediolateral location of the center of rotation (Fig. 2.2). By medializing the acetabular component, one reduces

the body moment arm, thus decreasing the amount of force generated by the abductors resulting in a decrease in the joint reaction force. However, if done excessively, this can reduce abductor muscle tension, which may need to be adjusted with the femoral offset. Thus, in order to restore the global offset (or the sum of the acetabular and femoral offset) in order to maintain adequate abductor muscle tension, you have to increase the femoral offset [30]. If the global offset decreases, the abductors' tension drops and becomes unstable. Conversely, if the combined offset increases, the abductors' tension will be excessive, potentially yielding more trochanteric pain, and there will be more torque force on the femoral stem, potentially leading to loosening [31] and peri-prosthetic fracture issues. When the center of rotation is lateralized compared to the native one, the femoral offset has to be reduced in order to conserve the original relationship between the greater trochanter and the pelvis. However, reduction of the femoral offset directly reduces the abductor lever arm, meaning abductor muscles have to produce more force in order to stabilize the pelvis. This consequently increases the joint reaction forces and wear at bearing surfaces. A geometric technique has been described to find the theoretical center of rotation by using the U landmark; a constant ratio has been observed between lateral position and height of the center of rotation and pelvis' width and height. Thus, it can be useful in cases where both sides are pathological [32].

**Cup orientation.** Hip prosthetic surgery entails removing the labrum and decreasing the head size for a THA case. Given this, the hip stability cannot remain the same. The native acetabulum covers the femoral head at  $170^\circ$ , whereas a prosthetic acetabular cup portrays a  $180^\circ$  design ( $170^\circ$  or less for resurfacing cups). Thus, cup positioning has to consider stability and avoid prosthetic impingement. Cup positioning must also take into account the influence on wear. Two parameters have to be considered for the position of the cup around its own center of rotation: its inclination and its anteversion. The **cup inclination** will play a role in the edge-loading phenomenon by influencing the CPCR (contact patch center to rim distance) and CPER (contact patch

edge to rim distance). The less inclined the cup is, the greater CPCR is in order to avoid edge loading. In addition, edge loading affects the lubrication regime and behavior of synovial fluid, which will further increase wear rates. With regard to **cup anteversion**, it is a major feature for prosthesis' stability, as a more anteverted cup will tend to avoid posterior dislocation. Having said that, cup version is not the only determinant of hip stability, as other factors (e.g., surgical approach, prosthetic design, head diameter, prosthetic neck anteversion) play a major role. Several methods have been described to position the cup during surgery and used either intra- (posterior and anterior rim, transverse acetabular ligament) and/or extra- (anterior pelvic plane) articular anatomical landmarks. Lewinnek initially described the safe cup implantation zone in order to reduce the risk of dislocation. It was defined as a  $15^\circ \pm 10^\circ$  anteversion and a  $40^\circ \pm 10^\circ$  lateral opening. However, better understanding of the lumbo-pelvic sagittal kinematics and the functional acetabular orientation has challenged the value of the Lewinnek safe zone when compared to a more personalized individual "safe zone" [33, 34]. Arthroplasty is progressively switching from a systematic to a patient-specific approach [33, 34].

**Femoral stem positioning.** Error in the implantation of the femoral stem will alter the restoration of the native hip anatomy and biomechanics. It's positioning in varus or valgus may either increase or decrease the femoral offset and abductor lever arm and potentially hinder optimal clinical outcomes. In the same manner, error in adjusting the stem version will modify the lever arms, potentially induce impingement, and affect the location of the contact patch between the head and acetabulum. Above all, the leg length discrepancy is clearly directly linked to the femoral stem cranio-caudal positioning and represents the second highest cause of litigation among US surgeons [35].

### 2.3.2 Relative to Components' Features

As aforementioned, component positioning can modify the native anatomy and biomechanics, but in addition, the components themselves differ

from the native anatomy features. On the femoral side, switching from a conchoid shape to a completely spherical shape changes anatomy. It has been shown that this special conchoid shape makes the joint less likely to sublux when compared to a true ball-and-socket joint. Furthermore, these shapes may contribute to the optimal stress magnitude and distribution. Adding to that the fact that the labrum is removed in prosthetic hip surgery, this emphasizes how anatomical concepts can be modified during hip surgery. In normal hip joint biomechanics, the labrum is crucial in retaining a layer of pressurized intra-articular fluid for joint lubrication and load support/distribution. Its seal around the femoral head is further regarded as a contributing factor to hip stability through its suction effect [36]. It is important in increasing the contact area, thereby reducing contact stress as well. For the head diameter, usual prosthetic head size ranges from 22 to 36 mm, whereas the native average head size is 49 mm for women and 53 mm for men. The main drawback of this size reduction is the stability impairment. It is well known nowadays the dislocation rates decrease when the femoral head size increases. Reduction of the femoral head size could also have a negative impact on proprioception. Another point is the head–neck offset modification; its main impacts are on the range of motion and the prosthetic impingement risk (additionally influenced by both cup positioning and femoral stem anteversion). Prosthetic impingement could lead to cup loosening (by increasing torque on the cup), prosthetic instability, increased wear, and liner fracture. A larger femoral head will offer a better head–neck offset and thus will reduce the risk of prosthetic impingement, in addition to facilitate a better range of motion. Several authors showed that this risk becomes negligible with a prosthetic femoral head  $\geq 32$  mm [37, 38]. The medial femoral offset is dictated by the femoral stem design, and its restoration is intimately tied to the prosthetic portfolio available. Another element to consider is the modification of Young’s modulus of elasticity inside the femoral shaft by using a 15–20 cm length titanium or CoCr alloy stem. It raises questions about proprioception modifications and above all, introduces the stress-shielding

concept. Mini-stem designs and resurfacing could lead to better proprioception by enabling natural femoral shaft deformation and elasticity, primarily for patients practicing impact sports (running). Nevertheless, scientific ways to evaluate that kind of hypothesis are limited. Moreover, using a conventional femoral stem, a part of the stress force is directly transferred to the femoral shaft, bypassing the metaphysis area. Nonnatural bone remodeling phenomenon is subsequently involved, modifying the initial bone architecture. Hip resurfacing avoids these drawbacks by preserving a close to natural stress distribution.

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## 2.4 When Is it Safe to Recreate the Constitutional Hip Anatomy?

Osteoarthritis can be primary or secondary. In primary cases, the patient’s anatomy is deemed as normal and may be reproduced, whereas for some cases of secondary osteoarthritis, the patient’s hip anatomy is considered abnormal, with articular cartilage damage being a consequence of impaired hip biomechanics. As Karimi et al. [39] mentioned, we have to be even more careful with the younger population as the percentage of secondary arthritis is higher among this group. The answer to the question “which constitutional hip anatomies may safely be restored when performing hip replacement?” still remains elusive.

It is important to be aware that most abnormal hip anatomies (CAM effect, abnormal combined anteversion causing pincer femoro-acetabular impingement, roof insufficiency) responsible for hip degeneration are automatically corrected when anatomically implanting modern component designs. Nonetheless, severely abnormal hip anatomy (e.g., atypical femoral and/or acetabular anteversion, protrusio acetabulum) may need to be corrected as they are potentially biomechanically inferior. For individuals with abnormal femur and/or acetabulum anteversion, one should: (1) assess the individual spine–hip relationship to understand the functional acetabular orientation and (2) perform 3D planning with simulated hip ROM, in order to predict the optimal implant