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Authors
Vendittoli, Pascal-André
Riviere, Charles
Hirschmann, Michael
et al.

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Why personalized surgery is the future of hip and knee arthroplasty: a statement from the Personalized Arthroplasty Society

Pascal-André Vendittoli[1,2,3], Charles Riviere[1,4], Michael T Hirschmann[1,5,6] and Stefano Bini[1,7]

[1]Personalized Arthroplasty Society
[2]Surgery Department, Hôpital Maisonneuve-Rosemont, Montreal University, Montreal, Québec, Canada
[3]Clinique orthopédique Duval, 1487 Boul des Laurentides, Laval
[4]Bordeaux Arthroplasty Research Institute - Clinique du Sport Bordeaux-Mérignac 04-06 rue Georges Negrevergne, Mérignac, France
[5]Department of Orthopedic Surgery and Traumatology, Kantonsspital Baselland, Bruderholz, Switzerland
[6]Clinical Research Group Michael T. Hirschmann, Regenerative Medicine & Biomechanics, University of Basel, Basel, Switzerland
[7]Department of Surgery, University of California, San Francisco, California, USA

Correspondence should be addressed to P-A Vendittoli
Email
pa.vendittoli@me.com

- Although hip and knee joint replacements provide excellent clinical results, many patients still do not report the sensation and function of a natural joint. The perception that the joint is artificial may result from the anatomical modifications imposed by the surgical technique and the implant design. Moreover, the joint replacement material may not function similarly to human tissues.
- To restore native joint kinematics, function, and perception, three key elements play a role: (i) joint morphology (articular surface geometry, bony anatomy, etc.), (ii) lower limb anatomy (alignment, joint orientation), and (iii) soft tissue laxity/tension.
- To provide a ‘forgotten joint’ to most patients, it is becoming clear that personalizing joint replacement is the key solution. Performing a personalized joint replacement starts with patient selection and preoperative optimization, followed by using a surgical technique and implant design aimed at restoring the patient’s native anatomy, creating optimal implant-to-bone stress transfer, restoring the joint’s native articular range of motion without imposed limitations, macro- and micro-stability of the soft tissues, and a bearing whose wear resistance provides lifetime survivorship with unrestricted activities. In addition, the whole perioperative experience should follow enhanced recovery after surgery principles, favoring a rapid and complication-free recovery.
- As a new concept, some confusion may arise when applying these personalized surgery principles. Therefore, the Personalized Arthroplasty Society was created to help structure and accelerate the adoption of this paradigm change. This statement from the Society on personalized arthroplasty will serve as a reference that will evolve with time.

Keywords

- hip
- knee
- arthroplasty
- personalized
- kinematic
- alignment
- outcome
- satisfaction
- forgotten joint

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Joint replacement surgery has evolved significantly since its conception. Despite initial failures, total hip and total knee arthroplasties (THAs and TKAs, respectively) have gained acceptance with ever-improving implant survivorship and patient satisfaction. Modern hip replacement has even been named ‘the operation of the century’ (1). Recently, thanks to developments in data science, biology, genetics, and many other fields of science, there has been a movement in patient care away from standardized procedures for all patients toward personalized medicine that considers the variability in the human condition and creates customized care plans designed to meet an individual’s specific needs. Personalized medicine has extended our understanding of human anatomy and fostered a more bespoke approach to surgery.

The ultimate aim of a joint replacement is for the joint to be as pain-free and functional as a native healthy joint; this state of affairs is sometimes referred to as a 'forgotten joint' (2). Despite notable success in implant survivorship, it can be argued that the current approach to total hip and knee arthroplasty has not fully achieved this aim. Patients naturally hope to undergo complication-free surgery with minimal postoperative pain and a swift recovery. Furthermore, they want to resume the leisure activities they enjoyed before the joint disease impacted their lifestyle (e.g. sports) and return to work promptly after surgery. For patients with physically demanding jobs (roofing, plumbing, firefighting, policing, etc.), being unable to resume work might force them to reorient their career path with potentially significant socioeconomic costs.

What is a personalized joint arthroplasty?

There is extensive anatomic variation across and between individuals (3, 4, 5, 6). It has been proposed that only through the precise restoration of individual anatomy through arthroplasty will surgeons restore a patient's clinical function to its healthy, prearthritic state and improve patient satisfaction. The improvement in the wear resistance of implants, their fixation methods, and the unprecedented advancement in navigation and robotic technology allow surgeons to achieve a more lasting and precise anatomical joint restoration with implants that have a reasonable chance of lasting a lifetime.

Additionally, patients may have specific social, medical, and/or psychological needs that need to be considered in their personalized surgical plan if the surgeon wishes to optimize the chances for an excellent outcome. For example, a patient's work, activities of daily living, leisure preferences, and expectations from surgery must be considered and allowed to influence the planning of a successful personalized total joint replacement.

A personalized arthroplasty should aim to restore/provide the following:

1. A natural joint perception (forgotten joint)
2. Restore 'functional' biomechanics (when native anatomy is not considered pathological)
    a. The native hip's center of rotation or the knee's kinematic axes
    b. Leg length equality
    c. Balanced joint lever arm
    d. Native joint surface orientation
    e. Native soft tissue tension
    f. Native kinematics and kinetics during activities
3. Appropriate stress transfer from implant to bone (minimizing problematic bone remodeling, osteopenia, and thigh pain)
4. Native articular range of motion
5. Macro- and micro-stability of the joint

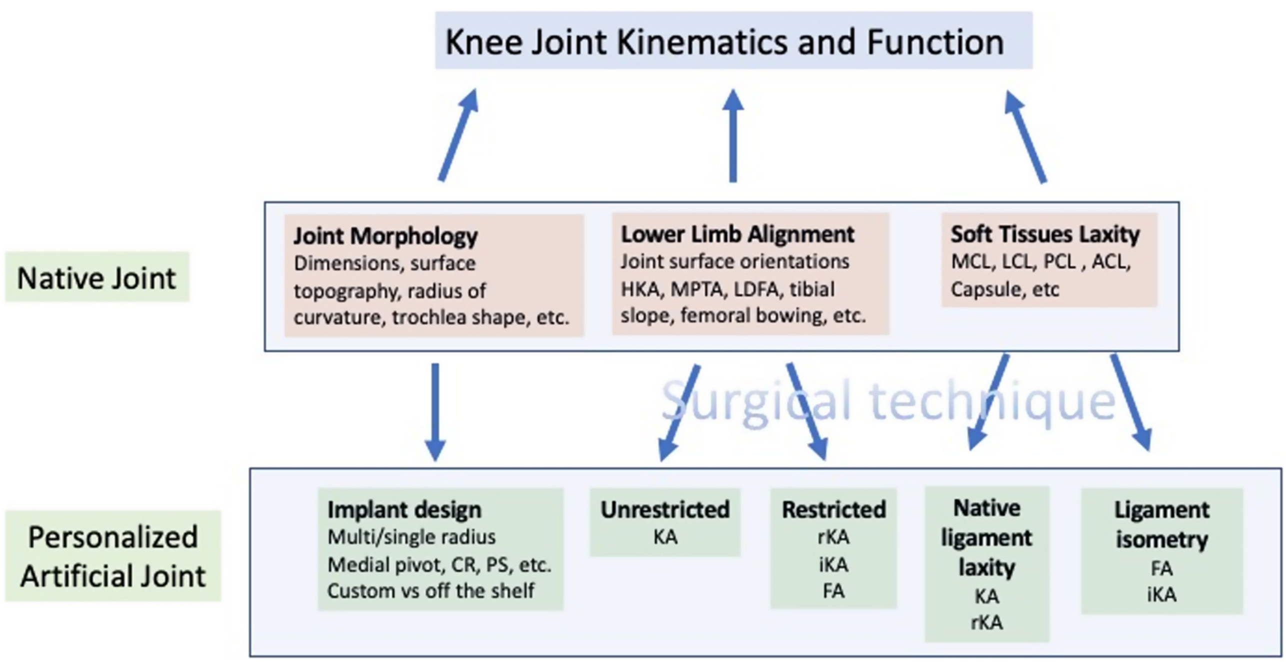

Figure 1
Essential elements of personalized knee arthroplasty to consider for optimal postoperative kinematics and function.

6. Bearing wear resistance and solid implant fixation that provides a lifetime implant survivorship with unrestricted activities
7. Rapid and complication-free recovery

A schematic description of a personalized arthroplasty is presented in Fig. 1 for TKA and Fig. 2 for THA.

Creating the forgotten joint

A patient's perception that their joint feels normal remains the ultimate but elusive goal of arthroplasty surgery. A validated simple questionnaire with five possible answers that assesses joint perception has been published (the Patient's Joint Perception questionnaire) (7). Using this simple questionnaire, at a mean of 68 months of follow-up, 52% of 257 large-diameter head (LDH) THA patients reported that their hip felt like a 'natural joint', despite the fact that 76% reported no limitations related to their LDH THA and only 1% reported major restrictions (7). On the other hand, assessing 100 TKAs at a mean of 41 months of follow-up, only 39% of the patients perceived their knee as a 'natural joint', 51% reported no limitation after their TKA and 13% had major restrictions (8). These clinical results suggest that there may be more gains to be made in TKA than THA as modern hip replacements have more consistently fulfilled the aim of achieving a 'forgotten hip'. Therefore, we believe that taking a personalized approach to knee arthroplasty surgery is likely to improve TKA results as well.

Restoring normal functional biomechanics

The anatomy and kinematics of the hip and knee are complex and poorly understood, particularly in the diseased state. This is because normal anatomy varies widely, and pathological changes increase this variability further. When hip and knee surgeries were introduced, instrument precision was poor, implant designs and materials were unreliable, and implantation errors frequently led to high implant failure rates. In the early decades of arthroplasty, the primary focus was on improving implant survivorship rather than reproducing normal anatomy and the perception of normal function.

Knee replacement

To simplify TKA operations, surgeons selected neutral femoral and tibial cuts to create rectangular flexion and extension gaps and a neutral mechanical axis. Codified under 'mechanical alignment', these targets were considered achievable, reproducible, and biomechanically favorable for the implants. As a result, individual 3D knee anatomy was not reproduced, and while implant survivorship improved, prosthetic joint function and perception were compromised. Bony anatomy modifications created by mechanical alignment were linked to frequent mediolateral and flexion–extension joint gap imbalances and patellofemoral dysfunctions

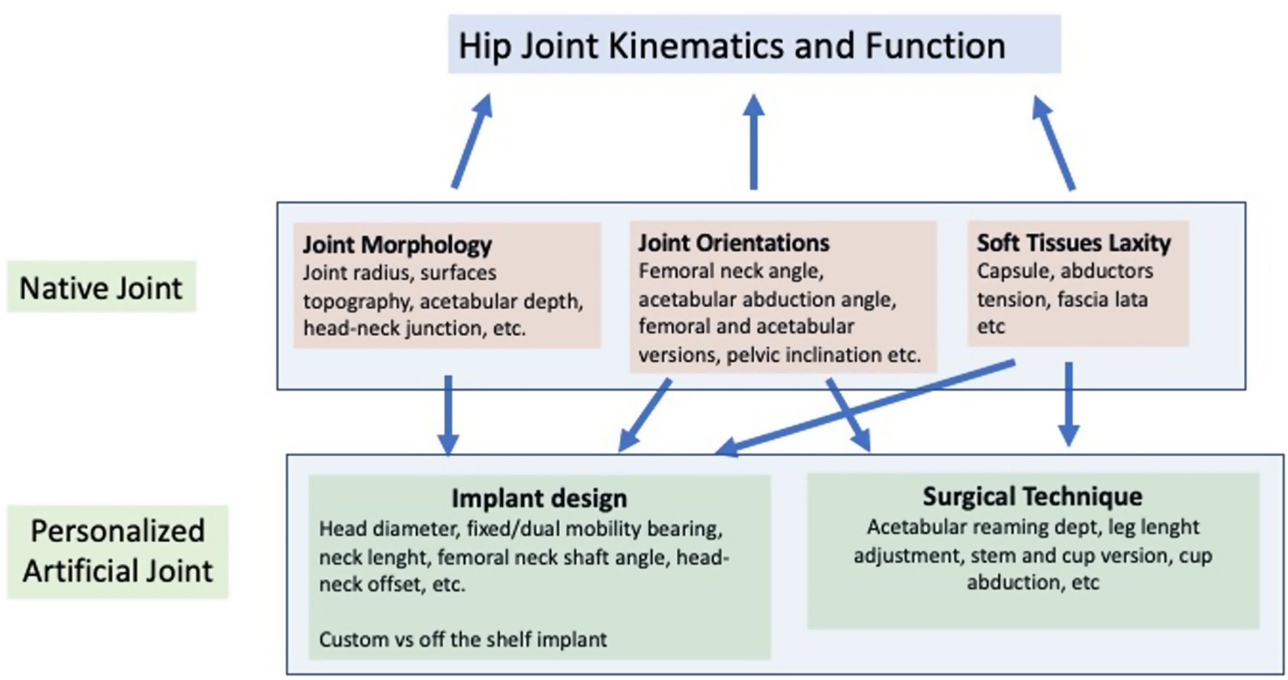

Figure 2
Essential elements of personalized hip arthroplasty to consider for optimal postoperative kinematics and function.

(9, 10, 11). Multiple soft tissue release techniques were developed to force the patient's soft tissues to adjust to the nonanatomical bone cuts (12). Personalized TKA surgical techniques are intended to solve the issues created by MA-TKA techniques. Personalized TKA considers the individual's variability restoring native knee anatomy and physiological soft tissue laxity as how to produce more natural knee joints, improve patient satisfaction and create a forgotten joint. As a pioneer in personalized knee surgery, Stephen Howell proposed the kinematic alignment (KA) technique (13). KA aims to restore native knee kinematics by simply resurfacing the knee surfaces and thereby recreating the knee's three kinematic axes, which are parallel and perpendicular to the native joint lines.

On the other hand, outlier anatomies are suspected to be inherently biomechanically inferior and potentially incompatible with current implant material and fixation methods (14). Keeping in mind the historical impacts of outlier alignments on TKA survivorship, Vendittoli proposed alignment boundaries to KA, named restricted KA (rKA) (15), and recommends a maximum variance from the neutral mechanical axis in the coronal plane for TKA. Therefore, Personalized TKA can be categorized into unrestricted and restricted component orientation. Restricted methods include rKA aiming at restoring native ligament laxities, inverse KA, and functional alignment, both aiming at ligament isometry (16). Whether we should restore all anatomies and native ligament laxities is still debated. We are transitioning from systematic techniques to a patient-specific approach that still needs to be fully defined and quantified (17). Whether one personalized technique is superior to the other or provides better patient outcomes is yet to be determined, and further studies are needed.

Hip replacement

In the earliest days of THA, bearing sizes were nonanatomical and partly due to the limitations of metallurgy at the time, there were limited options available for femoral stems that could replicate a patient's native biomechanics (neck angle, offset, stem anchoring in the diaphyseal area, etc.). It is likely that in THA, like in TKA, the precise restoration of the patient's anatomy may improve the prosthetic joint's stability, kinematics, function, perception, and longevity. Additionally, a better understanding of how an individual's native or pathologic dynamic acetabular orientation may impact clinical outcomes is currently being worked out (18). Following systematic implant orientation, patients with a stiff lumbar spine are at increased risk of prosthetic impingement and edge loading (e.g. wear, squeaking, dislocation, residual pain). It has been recently demonstrated that patients with prior spine fusions compensate by using an excessive hip range of motion (ROM) for activities of daily living ('hip user' patients). These patients may be preoperatively screened by measuring their sagittal posture, both standing and deep-sitting and planning acetabular component positioning accordingly. Specifically, the surgeon needs to personalize the surgical approach, choice of bearing, head diameter, cup orientation, and indications for alternative bearing surfaces such as dual mobility. The Bordeaux classification for spine–hip relationship and the concept of kinematic alignment for THA have been presented to help surgeons facing such complicated procedures to personalize their approach to THA.

The advent of precision technologies

One of the drivers of adopting MA-TKA principles was that it was reproduced reasonably accurately with manual instruments designed specifically for that purpose. Today, we can revisit the assumption. High precision in surgery is now possible due to newer technologies, such as computer navigation, patient-specific instrumentation (PSI), and robotics (19). These technologies may facilitate the individualized alignment of the implants to replicate and adapt to a patient's anatomy. Further study and refinement of these technologies will determine the best approach moving forward, considering each technique's surgical complexity, costs, and relative benefit for any given patient.

Few question that greater precision in surgery is important as it refers to the ability to reproduce a specific value consistently. However, improved precision in TKA achieved with computer-assisted surgery/robotics has notoriously not significantly improved clinical outcomes. Unfortunately, an increased surgeon's ability to achieve a specific target (precision) will not improve outcomes if the target is not appropriate (20). When these technologies were being introduced, most surgeons were aiming for a mechanical alignment, which we now believe to have been the wrong target for most of the knee (21, 22, 23, 24). Our technique is considered accurate when the targeted value is optimal. Therefore, a surgical technique should be accurate and precise in the ideal world. With a new target in mind of a personalized alignment, improved precision may reveal its value (14, 24, 25). Indeed, it has been stated that 'evolving beyond craft surgery is both inevitable and essential' (26). On the other hand, Howell showed that precision tools are not essential to achieve a precise KA TKA implantation (27, 28). As precision tools are expensive and not readily available to all, one can perform personalized knee joint surgery using the callipered measurement technique if the surgeon wishes to reproduce the patient prearthritic anatomy. However, the technique may not allow the adjustments required by restricted personalized alignment techniques (29).

It should be noted, however, that achieving patient-specific implantation with a nonanatomic prosthesis design solves only part of the problem. As most implants are designed around 'average' relationships between multiple axes and angles and do not take into account that in any one patient, these relationships may vary in a nonlinear fashion, the next logical step on the road toward personalized surgery is to provide access to custom implants that are designed to reproduce an individual's anatomy where it cannot be closely approximated with standard, off the shelf components.

The road to customized implants

The highly variable anatomy of the proximal femur may render reliable restoration of the native hip anatomy and biomechanics complex when performing THA (30). Over the years, hip resurfacing, increased implant sizes and shapes, short femoral stems, modularity of components, and LDH bearing were proposed to help restore native biomechanical hip parameters (31). However, in THA, customized implants are not of a major benefit to date for most patients. It is also true that in many cases of hip arthritis, the underlying anatomy was the primary cause of the diseased state to begin with and does not provide a model for subsequent restoration, unlike in the knee. On the contrary, underlying anatomy must be altered in many patients to create a functional, stable, and 'forgotten' joint. In these patients, modular implants have shown to be reasonably successful in restoring function and mobility.

Unlike in the hip, customization of total knee replacements has enjoyed some success. The anatomy varies by gender, ethnicity, and body type (32). Within these groups, there is further variation such that each individual has a unique knee geometry. This would suggest that a customized implant would be advantageous if one tries to replicate individual variations to perform personalized arthroplasty.

Switching from a one-size-fits-all mechanical alignment strategy to one of personalized alignment, off-the-shelf implants limit a surgeon's ability to reproduce prearthritic native anatomy in most patients (33, 34, 35, 36). The advantages of patient-specific implants for knee replacement include an optimized implant designed to fit and recreate native anatomy, thus preventing prosthetic overhang or undercoverage and providing instead the possibility to reconstruct anatomically, without compromise, both the relationship between the femorotibial and the patellofemoral joints. Furthermore, improved ligament balancing is much improved by avoiding ligament laxity due to asymmetric bone cuts. Restoring the native radii of curvature of the femoral condyles may avoid mid-flexion instability and improve kinematics and patellofemoral tracking. Although these customized implants help reproduce the native knee's anatomy and alignment, they still require the resection of the anterior and occasionally the posterior cruciate ligaments and the menisci. The cruciates and the menisci are not adequately replaced, and their absence negatively affects knee kinematics. A solution to reproduce truly normal knee kinematics may come from a patient-specific/custom implant design that replaces these structures (or retain them when they are healthy), which is precisely positioned, using advanced technologies (37).

Lifetime implant survivorship

THA and TKA implant survivorship should exceed the patient's life expectancy. Polyethylene wear-related biological reactions in young and active patients are no longer as much of a concern as they once were, with excellent survivorship offered by several modern bearings. For THA, ceramic-on-ceramic (CoC) implants offer greater scratch resistance and lower linear/volumetric wear rate than all other bearing options. They are associated with reduced wear-induced osteolysis, reduced cumulative long-term risk of dislocation, reduced corrosion of the head–neck modular junction, and lower revision rates. Evidence from the UK National Joint Registry in 2021 shows that uncemented CoC bearings have the lowest revision rates compared with metal-on-polyethylene (MoP) implants with the highest revision rates for head sizes above 36 mm. In a recent randomized, controlled trial (RCT) that compared the long-term implant aseptic revision rate of metal-on-conventional polyethylene with CoC implants, a survivorship rate of 96.9% was reported for CoC and of 76,3% was reported for MOP at a minimum follow-up of 21 years (38). Excellent implant survivorship has also been reported for ceramic heads on highly cross-linked polyethylene, although long-term follow-up is still pending. For the younger, active patient having a life expectancy of 20 years or more, modern bearing couplings provide a more reliable option than in years past. However, concerning TKA, the New Zealand Joint Registry database recently reported that the lifetime risk of requiring revision following knee arthroplasty was 22.4% in patients aged between 46 and 50 years at the time of the initial surgery (39). Data from the Clinical Practice Research Datalink in the UK showed that the lifetime risk of requiring revision surgery in patients who had THA or TKA over the age of 70 was approximately 5%, with no difference between men and women (40). The risk of revision increased for patients who had surgery younger than 70, with the greatest risk (35%, 95% CI: 30.9–39.1) observed for men in their early 50. Differences were observed between men and women, with women having a 15% lower risk in the same age groups. However, these data do not reflect the many improvements made in more recent years in implant design, fixation technology, and bearing surface mechanical properties.

Optimized and personalized perioperative care

Many of the recent advances in joint replacement surgery have focused on the optimization of perioperative care. It is well-known that specific conditions are linked to an increased rate of postoperative complications (41). For example, preoperative hemoglobin level below or equal to 120 g/L is associated with a 6- to 7-fold increase in the incidence of blood transfusion. Similarly, poorly controlled diabetes (HbA1c of >8%) is associated with higher wound complications and infections. The preoperative period provides a unique opportunity to optimize all modifiable risk factors. Both nursing and medical evaluations should identify and address patient habits, such as smoking and excessive alcohol consumption, and comorbidities, such as ischemic heart disease, arrhythmias, high blood pressure, sleep apnea, prostatic symptoms, venous insufficiency, DVT risk, and malnutrition or metabolic syndrome. We have learned that drugs prescribed to treat pre-existing conditions should frequently be continued before the surgery. A person with specialized knowledge of these conditions in concert with the anesthesia team should determine discontinuation and resumption of these drugs.

Concerning perioperative care, introducing principles of enhanced recovery after surgery (ERAS) and implementing arthroplasty-specific recovery pathways have had a dramatic, positive impact on patient outcomes (42, 43). A successful ERAS program requires multidisciplinary collaboration among anesthesiologists, surgeons, physiotherapists, nurses, and hospital administrators. In the future, perioperative care before and after total hip and knee arthroplasty will need to improve further if we are to obtain the ultimate goal of a pain- and risk-free operation. Improvements in pre- and postoperative care have had impressive downstream effects as well. It is now common in many high-volume centers for patients to be discharged home the same day as surgery with no reported increase in readmission rates when patients are appropriately selected and receive appropriate support following discharge. The advent of digital platforms and sensors designed to support and monitor patients at home during recovery is another step forward, driving the optimization and personalization of total joint surgery.

The limits of the personalized arthroplasty concept

There is some debate surrounding the general applicability of the personalized arthroplasty concept to the spectrum of arthritic phenotypes that a surgeon commonly treats (15, 44). This is particularly pertinent in cases where osteoarthritic disease has led to severe or noncorrectable knee anatomy. For example, there are situations where the disease process leading to an arthroplasty indication has created soft tissue stretching or contracture and where the patients have acquired extra-articular deformity affecting native joint kinematics and loads. Moreover, we should determine which anatomies reproduction might negatively affect the patient's joint biomechanics, increase bearing surface wear, and threaten the implants' fixation. In these cases, performing a personalized arthroplasty is more challenging and may require or benefit from compromises, restrictions, and soft tissue releases. As with other aspects of personalized arthroplasty, these new principles still need to be defined and validated.

For THA, childhood diseases like Perthes disease or developmental dysplasia, extra-articular deformity, hip fusion (spontaneous or acquired), and soft tissue dysfunction are obvious pathological anatomies that should not be reproduced during THA as the patient's hip joint was never 'normal' to begin with. However, there are situations where anatomical variations induce a different form or personalization, one in which the aim is to address or mitigate pathology elsewhere in the skeletal system or address underlying anatomical deformity. For example, the interrelation between the spine, pelvis, and hip was recently recognized as a critical factor explaining component impingement, limited ROM, and instability after THA with standard bearing surfaces in patients with fixed spinopelvic deformity. To personalize the surgical plan, it is important to preoperatively screen patients having poor spine–hip relationship (45). Surgeons can make use of forgiving LDH or dual mobility implants and/or adapt their acetabular component orientation according to the functional or kinematic cup alignment principles. Applying the recommendations for a functional implant alignment requires sophisticated preoperative 3D imaging techniques and intraoperative precision tools (precise acetabular component orientation). On the other hand, large diameter head (LDH), including dual mobility, is a much simpler solution (46). The supraphysiologic ROM offered by the large head–neck offset can compensate for patients' abnormal spinopelvic mobility and surgeons' imprecision. Furthermore, over a lifetime, spinopelvic mobility and parameters might change; LDH THA should sustain these unpredictable modifications.

Regarding TKA, an instructional review and classification system including six categories have been proposed: 1 – severe constitutional varus limb, 2 – severe constitutional valgus limb, 3 – extreme constitutional joint line orientation, 4 – patella maltracking, 5 – difficulty in estimating native knee anatomy, and 6 – acquired lower limb malalignment (44).

Personalized joint arthroplasty does not mean reproducing patient anatomy/pathoanatomy in all cases. Instead, it means offering the optimal surgical solution that addresses the patient's disease and utilizes current implant technology. Therefore, we need to recognize the patient's needs and the limitations of the surgeon and technology and find the best available option to optimize the patient's outcome.

Conclusion

It is an exciting time for surgeons to be performing joint replacements. The initial aim of hip and knee arthroplasty of providing a reliable joint replacement with good survivorship has been met. The focus has therefore shifted to improving patients' prosthetic joint perception and function, surgical experience, and overall satisfaction. New technologies providing sufficient surgical precision to consistently replicate native alignment and anatomy while preserving soft tissues and ligaments have opened new opportunities for current and future developments such as personalized joint reconstruction. We believe that a custom prosthesis precisely implanted to match patient anatomy, coupled with a holistic perioperative care model and advanced patient engagement platforms, will hopefully lead to the holy grail of joint replacement surgery: a forgotten or 'natural feeling' prosthetic joint.

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Author contribution statement
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