Computer-aided surgery meets predictive, preventive, and personalized medicine

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Received: 27 January 2017 / Accepted: 12 February 2017 / Published online: 7 March 2017
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Abstract Computer-aided surgery (CAS) is now nearly 30 years old. It has brought to surgery a variety of tools, techniques, and paradigm changes that have had an impact on how surgeries are planned, executed, and evaluated. In this review, we examine the predictive, preventive, and personalized medicine (PPPM) aspects of CAS. We present a brief history of CAS, summarize its the state of the art, and discuss current trends and future developments related to PPPM. Of the three Ps, we note that the most important impact of CAS is on Personalization, in all the steps of the surgical treatment: preoperative planning, intraoperative execution, and postoperative evaluation. Prediction in CAS is reflected in the preoperative evaluation of the various surgical options and in the evaluation of the possible surgical outcomes. Prevention in CAS is related to intraoperative execution, to help prevent possible surgical complications. We foresee that CAS will play an increasingly important role in PPPM in the coming years.

Keywords Computer-aided surgery · Medical robotics · Surgical navigation · Predictive preventive personalized medicine

Brief history of CAS

Computer-aided surgery (CAS) is an interdisciplinary field whose aim is to develop new computer-based methods to assist surgeons in performing surgeries. CAS started in the late 1980s, with the introduction of three key technologies: surgical planning, surgical navigation, and surgical robotics [1–5]. Surgical planning allows surgeons to plan various aspects of the surgery, including the determination of access points, implants selection and position, and the quantification of 3D anatomical shapes and their relative positions based on volumetric scans (CT/MRI) acquired prior to surgery. Surgical navigation provides a real-time view of the patient anatomy and tracked surgical instruments with respect to preoperative/intraoperative images or diagrammatic representations that convey localization information. Surgical robotics provides mechatronic assistance to surgeons for precise targeting, dexterous manipulation, and exact execution of surgical gestures.

The first CAS systems were a navigation system for frameless stereotactic neurosurgery [3], a robotic system for total hip replacement in orthopedics [4], and a tele-operated robotic arm for holding laparoscopic camera and instruments [5]. The concept of frameless stereotaxy and the first neuronavigation system was developed by Roberts et al. in the late 1980s. Roberts' device consisted of an operating microscope whose spatial location was tracked by a sonic digitizer. Watanabe et al. later developed multi-axis mechanical measuring arms equipped with potentiometric angular sensors and video equipment for digitizing of CT scans from conventional films. Taylor et al. developed ROBODOC®, a customized industrial active robot for total hip replacement designed to optimize the bone/implant interphase by machining the implant cavity [4]. The system includes a preoperative

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planning module that allows surgeons to select the size and position of the acetabular cup and femoral stem based on automatically built 3D surface models of the pelvis and hip joint bone from a preoperative CT scan. Based on this plan, the software automatically generates a specific machining plan for the femoral stem cavity, which is then executed during surgery after pin-based contact registration between the patient and the plan. The first human surgery took place in 1992.

The early to mid 1990s saw the development of prototype systems in orthopedics, neurosurgery, maxillofacial surgery, and laparoscopic surgery. Early commercial systems include ROBODOC® for total and revision hip replacement, NeuroMate® for robotic frameless stereotactic neurosurgery [6], and the AESOP® arm for holding a laparoscopic camera and/or instruments. ROBODOC® became a commercial product in 1995 (Integrated Surgical Systems, owned since 2008 by Curexo Technology Corp) [7]. NeuroMate® was commercially introduced in 2001 by Renishaw Mayfield SA. AESOP® was introduced in 1994 and commercialized by Computer Motion Inc., which merged in 2003 with Intuitive Surgical, the manufacturer of the DaVinci® robot [8]. In parallel with these industrial developments, academic and scientific interest also increased. In 2000, the International Society for Computer Aided Surgery was established and has held yearly meetings since [9].

The early and mid 2000s witnessed a raise in the introduction of commercial systems and in the publication of small- and medium-size clinical studies with the first results of the use of CAS systems in the clinical routine. The late 2000s featured a slow commercial consolidation period, with the introduction of additional surgical robots, e.g., SpineAssist®, a patient-mounted miniature system for pedicle screw insertion in spine surgery [10, 11] (Mazor Robotics), and Mako®, a semi-active robot for uni-compartmental knee arthroplasty [12, 13] (Mako Surgical Corporation, now Stryker). Larger and more specific comparative clinical studies, multi-center studies, and meta-studies appeared in the literature. Mature image processing and surgical planning software, image-based navigation systems, and tele-operated robotics systems also appeared in this period.

A notable development of the last decade is the DaVinci® robotic system [8] (Intuitive Surgical), a tele-operated multi-arm system which has revolutionized minimally invasive laparoscopic surgery. The system consists of several robotic arms that can hold the video camera and various standard and custom surgical instruments. DaVinci® has been an enabler to a variety of minimally invasive laparoscopic surgeries in gynecologic, urologic, colorectal, gastrointestinal and thoracic surgeries. With over 3500 systems and three million surgeries performed to date in 64 countries, it is by far the CAS system that has had most impact on surgery at the beginning of the twenty-first century.

CAS and PPPM: state of the art and state of practice

CAS technology and its methodologies have come of age and are becoming more pervasive in medicine and more particularly in surgery. CAS technologies are now present in nearly all aspects of the patient treatment cycle. In addition, a distinctive feature of CAS systems is their integrative nature and their influence on the overall patient treatment process and surgical workflow. In the following, we review the state of the art and the state of practice of CAS with respect to each one of the three Ps of PPPM: prediction, prevention, and personalization [14].

Personalization Of the three Ps, we note that the most important impact of CAS is on Personalization. CAS has increased Personalization in preoperative planning, intraoperative execution, and postoperative evaluation. Preoperative planning allows the customization of the surgery to the specific needs of the patient. Nowadays, nearly all of the surgical procedures are planned using images acquired before the surgery, with a notable increase in volumetric scans, e.g., CT and MRI imaging. CAS technologies include 3D visualization, 3D anatomical modeling, and advanced analysis. For example, in orthopedic surgery, CAS systems support the selection of joint replacement implants and fracture fixation hardware and their optimal positioning based on the patient bone geometry and bone quality, e.g., osteoporosis. Advanced biomechanical analysis includes patient-specific kinematic and dynamic simulations of knee and hip joints, bone loading analysis, and fracture risk analysis based on the patient CT data. In minimally invasive stereotactic neurosurgery, the planning helps surgeons determine the best access location on the skull and safest insertion trajectory for biopsies and therapy delivery. The availability of CAS technology allows clinicians to explore more treatment options and surgical scenarios. In some cases, e.g., radiosurgery, the individualized treatment is not possible without CAS technology.

Surgery is, by definition, personalized. CAS technology supports specific surgical gestures such as suturing implant and surgical tool positioning, drilling, and cutting by providing passive, semi-active, and active systems such as 3D printed personalized cutting jigs, hand-held smart tools, and tele-manipulated robotic arms. Real-time intraoperative navigation technologies help guide the surgeon to the specific patient anatomy and determine in real time the location of tools and implants without having to acquire new images. A key contribution of CAS technologies to the personalization of the surgical workflow is the integration of preoperative planning and intraoperative execution, thereby enhancing the personalization and allowing plan modifications on the fly. CAS also plays a role, albeit more limited, in postoperative evaluation and treatment follow-up. Currently, CAS support for personalized follow-up mostly consists of quantitative radiological evaluation based on postoperative images.

Prediction Prediction in CAS is reflected in the preoperative evaluation of the various surgical options and in the evaluation of the possible surgical outcomes. CAS supports predictive medicine by improving preoperative planning and postoperative evaluation. Preoperatively, it allows the exploration of alternatives based on advanced simulations. Advanced analysis can help estimate the risk of a procedure or the expected performance of an implant. For example, methods for optimal trajectory planning for keyhole neurosurgery help select the safest cannula insertion trajectory based on a model of the patient brain and vascular structures constructed from the patient CT and MRI scans [15]. Another example is the selection of the best fixation hardware and its configuration for bone fracture surgery [16, 17]. A 3D two-hand haptic-based system provides the surgeon with an interactive, intuitive, and comprehensive, planning tool that includes 3D stereoscopic visualization and supports bone fragments model creation, manipulation, fracture reduction and fixation, and interactive custom fixation plate creation to fit the bone morphology. Advanced biomechanical loading analysis helps determine which fracture fixation strategy is best under different loading conditions.

Postoperatively, CAS technologies support surgical outcome evaluation and help in assessing the success of the intervention and the need for revision surgery. To date, very few (if any) CAS tools are capable of postoperative prediction. This is mostly due to our limited understanding of complex biological processes, e.g., cell and bone regeneration, which precludes the development of reliable patient-specific simulation models.

Prevention Prevention in CAS is mostly related to the intraoperative execution. CAS technologies help foresee undesirable scenarios and prevent possible surgical complications. Prevention is achieved in the preoperative planning stage by considering various surgical alternatives, and implant choices and locations, as described above. Surgical simulators, such as those of 3D Systems (formerly Symbionix) [18] allow the surgeon to train for a surgery using patient data. This preoperative rehearsal can be considered a preventive measure. Overall, we see that for surgery, Prevention is closely related and associated to Prediction. CAS technologies for preventive surgery have not yet been developed.

We conclude that, of the three Ps, the most important impact of CAS is on Personalization. Prevention and Prediction are closely related and benefit most from CAS-related preoperative planning tools. The integrative nature of CAS technologies provides the technological support for surgical total quality control (TQM), in which the surgical workflow and the decision-making process is fully documented and can be analyzed to evaluate, personalize, and change the patient treatment process.

Trends and perspectives

We foresee that CAS will play an increasingly important role in PPPM in the coming future. The brief analysis above indicates that the Personalization aspect will benefit most. New CAS technologies include advanced anatomical and physiology modeling, simulations, surgeon training, and smart instruments. We foresee that with the advent of advanced anatomical and physiology modeling and simulation, Prediction and Prevention will increase in role and impact.

CAS has led to some paradigm changes in some cases, while it has had a more modest impact in others. In neurosurgery, frameless stereotactic navigation is state-of-practice. In minimally invasive abdominal surgery, the DaVinci® robotic system has had a profound influence on laparoscopic surgery, becoming the state-of-practice in some procedures and enabling new ones despite the high cost of the system and of its use. In orthopedic surgery, the change has been incremental [19, 20]. As a consequence, the effect of CAS on PPP has been varied; we expect them to continue to be so.

CAS technologies have obviated the need to revise and extend existing clinical and technical evaluation procedures. For example, currently, there is no consensus on how to evaluate the accuracy of surgical procedures [21]. While surgical accuracy is multifactorial, the lack of a standardized evaluation protocol affects the ability to compare clinical results from different hospitals using different surgical protocols, tools, and technologies. This in turn hampers the progress of PPPM. The CAS community is by now well aware of this shortcoming, and efforts are underway to develop protocols and reporting standards.

To conclude, we expect that the coupling of advanced diagnostics and treatment methods with CAS technologies will provide an important step forward towards PPPM, as envisioned in the position paper by Golubnitschaja et al. [14], for the benefit of all.

References

1. Joskowicz L. Modeling and simulation. In: Intraoperative imaging and image-guided therapy, Jolesz FA, editor, Springer Science. 2014; pp 49–62.
2. Mezger U, Jendrewski C, Bartels M. Navigation in surgery. *Langenbeck's Arch Surg.* 2013;398(4):501–14. doi:[10.1007/s00423-013-1059-4](https://doi.org/10.1007/s00423-013-1059-4).
3. Enchev Y. Neuronavigation: genealogy, reality, and prospects. *Neurosurg Focus.* 2009;27(3):E11. doi:[10.3171/2009.6.FOCUS09109](https://doi.org/10.3171/2009.6.FOCUS09109).
4. Taylor RH, Mittelstadt BD, Paul HA, Hanson W, Kazanzides P, Zuhars JF, et al. An image-directed robotic system for precise orthopaedic surgery. *IEEE Trans Robot Autom.* 1994;10(3):261–75.

5. Begin E, Gagner M, Hurteau R, Santis S, Pomp A. A robotic camera for laparoscopic surgery: conception and experimental results. *Surg Laparosc Endoscop*. 1995; 5611.
6. NeuroMate robot. Renishaw. Web site: <http://www.renishaw.com/en/neuromate-stereotactic-robot-10712>.
7. ROBODOC. Curexo Technology Corporation. Web site: <http://www.robodoc.com/professionals.html>.
8. DaVinci robot. Intuitive Surgical. Web site: <https://www.intuitivesurgical.com/>
9. ISCAS: International Society for Computer Aided Surgery. Web site: <http://www.iscas.net/>.
10. Shoham M, Lieberman IH, Benzel EC, Zehavi E, Zilberstein B, Roffman M, et al. Robotic assisted spinal surgery: from concept to clinical practice. *Comput Aided Surg*. 2007;12(2):105–15.
11. SpineAssist and Renaissance robots. Mazor Robotics. Web site: <http://www.mazorrobotics.com/>.
12. Roche M. Robot assisted unicompartmental knee arthroplasty: the MAKO experience. *Clin Sports Med*. 2014;33(1):123–32.
13. Mako robot. Stryker. Web site: <http://www.stryker.com/>.
14. Golubnitschaja O, Baban B, Boniolo G, Wang W, Bubnov R, et al. Medicine in the early twenty-first century: paradigm and anticipation - EPMA position paper 2016. *EPMA J*. 2016;7:23. doi:10.1186/s13167-016-0072-4.
15. Troppe M, Shamir RR, Joskowicz L, Medress Z, Rosenthal G, Maier A, et al. The role of automatic computer-aided surgical trajectory planning in improving the expected safety of stereotactic neurosurgery. *Int J of Comput Assist Radiol Surg*. 2015;10(7): 1127–40.
16. Kovler I, Joskowicz L, Kronman A, Weill Y, Salavarría J. Haptic computer-assisted patient specific preoperative planning for orthopaedic fracture surgery. *Int J Comput Assist Radiol Surg*. 2015;10(10):1535–46.
17. Peleg E, Beek M, Joskowicz L, Liebergall M, Mosheiff R, Whyne C. Patient specific quantitative analysis of fracture fixation in the proximal femur implementing principal strain ratios: method and experimental validation. *J Biomech*. 2011;43(14):2684–8.
18. 3D Systems (formerly Simbionix) surgical simulators. Web site: <http://simbionix.com/>.
19. Joskowicz L, Hazan E. Computer aided orthopaedic surgery: incremental shift or paradigm change? *Med Image Anal*. 2016;33:84–90.
20. van der List JP, Chawla H, Joskowicz L, Pearle AD. Current state of computer navigation and robotics in unicompartmental and total knee arthroplasty: a systematic review with meta-analysis. *Knee Surg Sports Traumatol Arthrosc*. 2016. doi:10.1007/s00167-016-4305-9.
21. Cartiaux O, Jenny JY, Joskowicz L. Accuracy of computer-aided techniques in orthopaedic surgery: how can it be defined, measured experimentally, and analyzed from a clinical perspective. *J Bone Joint Surg*. 2017. In press.