Computer Assisted Orthopaedic Surgery: Past, Present and Future:

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Abstract:

Computer technology is ubiquitous and relied upon in virtually all professional activities including neurosurgery which is why it is baffling that it is not the case for orthopaedic surgery with less than 5% of surgeon using available computer

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technology in their surgeries. In this review, we explore the evolution and background of computer assisted orthopaedic surgery (CAOS) delving into the basic principles behind the technology and the changes in the discussion on the subject throughout the years and the impact these discussions had on the field. We found that industry had an important role in driving the discussion at least in knee arthroplasty a leading field of CAOS with the ratio between patents and publications increased from approximately 1:10 in 2004 to almost 1:3 in 2014. The adoption of CAOS is largely restrained by economics and ergonomics with sceptics challenging the accuracy and precision of navigation during the early years of CAOS moving to patient functional improvements and long term survivorship. Despite this, the future of CAOS remains positive with new technologies such as improvements in image-guided surgery, enhanced navigation systems, robotics and artificial intelligence.

Keywords: Computer assisted orthopaedic surgery, navigation, robotics, knee surgery, imaging technology, registration, review.

Introduction:

Computer technology is ubiquitous and relied upon in virtually all professional activities. Confounding this is orthopaedic surgery where less than 5% of surgeons in the USA, Europe and Asia are using computer-assisted technologies routinely [1]. Although first introduced in the 1990s [1]. Computer assisted technology in orthopaedic surgery, or more simply Computer Assisted Orthopaedic Surgery (CAOS), is still not commonplace compared to un-assisted, conventional orthopaedic surgery.

It is currently predicted that a $1,000 computer will be able to carry out the same number of calculations per second as the human brain by 2025 [2]. Will this mean that computerised systems will exceed surgeons' skills, not only diagnosing and assessing patients but, more importantly, in surgical accuracy and precision even in complicated cases such as complex trauma or reconstructive surgery? According to Moravec [3], contrary to traditional assumptions, high level reasoning requires relatively little computer power, whereas low-level sensorimotor skills require enormous computational resources. Therefore CAS may solve some of the surgeon's task but not all. Furthermore, is a demand for enhanced accuracy warranted? After all, one of most commonly discussed issues with CAOS is the impact that accuracy of computer-assisted surgery has had on the outcomes of surgical procedures.[4]

It may be considered somewhat surprising therefore, at a time of incredible technological progress, with the advent of virtual and augmented reality, big data analysis and artificial intelligence, that the computer still struggles to make its way into all orthopaedic theatres of the world. Consequently, in this paper, we review questions regarding the paradoxical apathy towards the possible improvements of patient outcome through the use of CAOS and its impact CAOS on the mainstream principles and concepts in the orthopaedic forum.

In this article, we will outline some of the definitions related to CAOS and review general principles and key advances in today's state-of-the-art CAOS. Afterwards, we will describe CAOS historical background before delving into the impact that CAOS has had on the general “orthopaedic forum” and the way it approaches diagnostic and therapeutic guidelines, focussing the discussion on knee and hip replacement surgeries. Finally, we will speculate on future directions and offer our conclusions.

A few definitions:

Computer-assisted orthopaedic surgery (CAOS) includes all kinds of computerised tools, devices and instrumentations, such as robotic assisted or navigation technology, but also patient-specific instrumentation and even sensors. These are all used for, not only assisting the surgeon in augmenting surgical procedures, but also for providing hitherto unavailable quantitative data, measuring data not seen and sometimes not known by the surgeon which could help fine tune the surgery to an individual profile.

Three major components are common to any of these systems, as described in Zheng and Nolte’s excellent review paper published in 2015 [5].

- The first component is a *therapeutic object* which is the target of treatment. For instance, it can be a joint to replace or a tumour to resect in a specific patient.
- The second component is a *virtual object* which is the virtual representation of any object that the surgeon wants to implant (e.g. joint replacement) or resect (e.g. oncologic lesion) at any place of the patient’s body.
- The third component is a *navigator link* between these two objects.

CAOS technology offers a multitude of devices and complex mathematical algorithms to manipulate virtually, not only the patient's anatomy, but also any surgical tools and implants in real time. For instance, a 3-dimensional CT image of a patient's hip can be seen and assessed virtually on a monitor, whilst at the same time overlaying a perfectly fitting cup for simulation purposes [6,7]. During the preoperative planning phase, the *navigation link* is the software programme enabling virtual manipulation of both *the therapeutic and virtual object(s)* (hip anatomy and cup replacement). This concept of virtual simulation is applicable to any system using image-guided technology either preoperatively or intraoperatively [8]. Intraoperatively, the *navigation link*, such as a navigator or robot, allows the actual tracked object, e.g. a cutting tool, to be guided into the matched anatomy. This model also works for image-free computer-assistance following intraoperative data collection and registration of the "surgeon-defined anatomy", which generates the *therapeutic object* [9, 10].

General principles

All CAOS systems positioned near patients for surgical assistance follow four outline steps: Setup, Registration, Planning and Execution (Figure 1). The order of these stages depends on whether an a priori image is part of the workflow and used for planning. If so, the order is Planning, Setup, Registration, Execution. However, if planning is interoperative, the order of the steps is as before.

- *Set-up* refers to the initialisation process where the important objects are placed and identified within the operation space: trackers are fixed to suitable bony structures of the patient, and the data-capturing object(s) (e.g. camera and/or robot) are placed in theatre around the patient.

- *Registration* refers to prescribing the coordinates, in system-space, of important anatomical landmarks, and either registering them to a prior 3d image, or using them to define the therapeutic object (i.e. anatomic structure) directly.
- In *Planning* the intended aim of the procedure is prescribed. In CAOS, this is the definition of the ideal position of the *virtual object* within the *therapeutic object*. This stage could be done either pre-operatively using medical imaging technology or intra-operatively using image-free navigation or intraoperative imaging technology.
- *Execution* is self-explanatory. In CAOS, the level of agency for the surgeon varies depending on the type of system. In navigation technology, the surgeon is in full control of the surgery allowing for deviation from the initial plan whereas in robotic technology, the surgeon follows a presurgical plan typically without deviation.

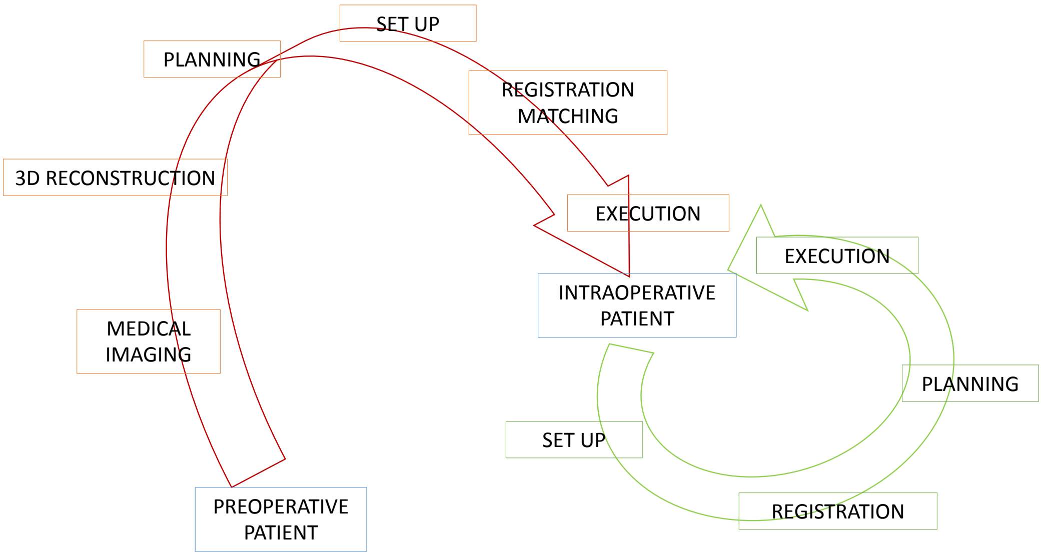

Figure 1: General principles: Image-guided (in red) versus image-free (in green) CAOS systems.

Indeed, it all starts from the patient's anatomy, which is analysed and assessed using imaging technology either pre-operatively (red arrow) or intra-operatively (green arrow). From there, a series of complex algorithms provide the surgeon and surgical team a 3-D reconstruction of the *therapeutic object* [for instance, the hip] and overlay it in real time into a *virtual object* (for instance a cup replacement). The surgical team or the surgeon can manipulate, in real time, both the *therapeutic object* and the *virtual object* in order to plan the surgery. This can be done pre-operatively, or intra-operatively [5] Once the planning is completed, then the surgeon or the surgical team can upload the planning and consequently navigate or robotically assist the planned surgery.

The CT-free or image-free navigation concept removes the image processing planning and matching so the surgeon and the surgical team are building up intra-operatively the *therapeutic object* (i.e. an abstract of the patient's anatomy) directly from the patient's anatomy (green arrow) (see figure 1). The built frame of reference is assembled virtually with a series of relevant anatomical or kinematical landmarks to create the *therapeutic object*. Then, any calibrated tools (*virtual object*) are superimposed to the created therapeutic object to execute intraoperative plan.[10][11]

Whatever computer-assisted system is used, *registration* is one of the core principles and a compulsory process that any CAOS system requires to work. Accuracy and precision are at the centre of the CAOS project with the promise to reduce outliers and improve functional and clinical outcomes and the quality of registration is fundamental to reach trueness and precision in CAOS. [4]

Any registration technique is basically trying to either build a patient-specific frame of reference as an abstract of the patient’s anatomy [e.g. image-free navigation] or to collect enough anatomical landmarks to match the pre-operative or the intra-operative imaging model(s). Any registration process requires DRB (digital rigid bodies) which need to be rigidly fixed to a bony structure in order to capture either an anatomical abstract [e.g. image-free navigation] or a complex anatomical model [e.g. image-based navigation]. It is important to mention that robotic-assisted technology also relies greatly on the registration technique and probably needs it more than in navigation because the surgical tasks are performed through robotic tools and not by surgical hands. [1,5,12]

In image based systems the ultimate goal of registration is to fuse or overlap the patient’s anatomy with any sort of medical imaging modalities. Several kinds of imagery can be used, such as CT scans, MRI scans or combined[13] and even ultrasound [14]. On the other hand, intra-operative registration of intraoperative anatomical landmarks can also be matched to statistical shape models using generic bony shapes or anatomic atlases. [15]

The complex mathematical algorithms applied to registration processes are mainly divided in four different modalities.

- Fiducial-based registration: this has not been very well accepted because it involves the use of additional surgical steps prior to the main one with the risk of local inflammation, infection and pain. [16]

- Landmark-based registration: which has been favoured because it requires only the use of a calibrated probe or pointer intra-operatively, defining relevant anatomical landmarks. However, this process can occasionally be tedious and time-consuming.[17]
- Shape-based registration: this is very close to so-called “bone morphing”, which requires data collection of painted surfaces of the bone and using mesh linking all these points to aggregate them all and build up 3-D model surface(s), which could then be matched to the pre-operative 3-D image reconstruction. [18]
- Finally, Intensity-based registration used mainly in fluoroscopy registration. This last technique allows the reduction of radiation dose during surgery because after completing registration and matching it is not necessary to take any further image intensifier shots during the surgical procedure. [19] This last modality is mainly used in spine and trauma surgery.

This registration process requires precalibrated tools, such as probe or pointer with various forms and designs all utilised to collect landmarks for the above registration modalities. [9] The surgical calibrated probe is to intra-operative registration, what the computer mouse is to the computer-assisted planning.

<u>Key advances and state-of-the-art in the field of CAOS at the present:</u>

CAOS systems can be divided into three different categories using potentially three different registration technologies [49].

- Active systems are autonomous, e.g. Robodoc® [50]

- Semi-active systems utilise handheld or controlled forced robotic assisted devices, e.g. the MAKO® [46,51].
- Passive systems only provide guiding information but no direct action, e.g. OrthoPilot® (Aesculap/BBraun, Germany) [52]

All three categories of systems can use different registration technologies:

- Pre-operative image technology, such as CT scans, MRIs, to assess specifically the therapeutic object (e.g. MAKO®). [53,54]
- Intra-operative medical imaging, such as fluoroscopy (image intensifier) commonly used in trauma and spine surgery, e.g. FluoNav-Medtronic® (Surgical Navigation Technology, USA) [55]
- CT-free or image-free technology, also called “surgeon defined anatomy”, e.g. NavioPFS® [56].

Any combination between these three categories and three modalities is theoretically possible. In reality, there are still a few combinations which are not on the market. To our knowledge, there are no active robots using fluoro-based registration nor any combined with image-free technology, otherwise the other combinations are already on the market.

Background and history

If the computer had existed at the beginning of the 20th Century, computer-assisted surgery would have been invented by Clarke and Horsley in 1906 [20]. These two researchers published and patented in 1908 a stereotactic frame and instrument for reproducible and systematic “navigation” in the monkey cerebellum based on external visible landmarks. This very same concept was used later with orthogonal X-rays by E. Spiegel in 1947 [21]. Much later in 1985, the PUMA robot (Programmable Universal Machine for Assembly) was coupled with a stereotactic frame and was applied to neurosurgery [22]. Robotic-guided surgery based on pre-operative 3D computer tomodensitometry planning was FDA approved in 1987 (NeuroMate, Integrated Surgical Systems, Inc.) [23], eighty years after Clarke and Horsley’s original article. Neurosurgeons embraced the technology, keen to develop safe options to reduce brain damage caused by invasive surgery during stereotactic surgery. In 2004, McBeth et al. stated “*The introduction of robotically assisted surgery has provided surgeons with improved ergonomics and enhanced visualization, dexterity, and haptic capabilities*” [24]. In the late eighties, ENT surgeons used image-guided technology to plan and guide complex reconstruction, but this did not disrupt the field as it has done in neurosurgery [25, 26]. For many years, neurosurgeons and orthopaedists have been performing both spine surgery. New developments in spine instrumentation, such as transpedicular screw fixation, gave rise to computer assisted technology in the field. Teams spread across the world in Switzerland (Bern), the USA (Detroit, Memphis) and France (Grenoble) simultaneously, developing technology to guide pedicle screw surgery. [12]

Since Hounfield’s [27] and Lauterbur’s [28] initial works on CT and MRI technology respectively, tremendous progress has been made in not only new diagnostic tools but also in computer-assisted 3D reconstruction [29]. Mathematical algorithms combined with new hardware, facilitated patient-specific planning, matching, modelling, intraoperative registration and intraoperative guidance [1]. Computer-assisted design (CAD) and computer-assisted manufacturing (CAM), in the orthopaedic world, expedited “custom-made implants”. Developed in the early 1980s by Aldinger et al. [30] to design perfectly fitting, patient-specific femoral stem implants [30], this concept is still used routinely for complex joint reconstructions in hip revisions, or for oncology cases during which surgeons perform large skeletal resections. [31].

Instead of creating bespoke implants to match the patient’s anatomy, the concept of machining the patient’s anatomy to facilitate using standard implant sizes was advanced. This development produced the first ever computer-assisted technology system in orthopaedics, Robodoc® (Curexo Technology, Fremont, CA), first used on humans in 1992 [32]. Robodoc® was an “active robot” or “autonomous robotic device” which excluded the surgeon from the task of rasping the femur to enlarge the intramedullary canal to fit the femoral stem in total hip replacement (THR). Following this came “semi-active robotic technology”, “controlled-forced robotic technology” or “haptic controlled technology” in which the surgeon was in charge in controlling a handheld device. Acrobot® (Acrobot Company Ltd, London, U.K.) was the first of this generation and was used for UKA surgery [33].

Paradoxically, navigation technology in orthopaedics came after robotics was introduced. The first CT-based navigation system was developed and used in 1994 in Pittsburgh by DiGioia and his team, who performed a computer-assisted guided hip cup replacement [34]. Other teams from all over the world worked on similar image-based navigation systems, such as in Japan for image guided hip replacement [35], in Switzerland for peri-acetabular reconstructions [36] or in the UK for femoral neck fractures [37].

Image-free or CT-free navigation, also called “surgeon-defined anatomy” technology, came in the early nineties with ACL reconstruction [38]. The first computer-assisted total knee replacement (TKR) system, based on similar concepts, was performed in 1997 [39,40,41]. In the same year, individual templates, also named patient specific instrumentation (PSI) or patient-specific-jigs, were introduced by Radermacher and later revived by Hafez [42,43].

More recently there has been an increase in the number of robotic orthopaedic technologies, with one of the front runners being MAKO® (Mako Surgical Corp., Florida, U.S.) [44], but many others have followed, such as ROSA® (Medtech, Montpellier, France) [44] and NavioPFS systems (Blue Belt Technologies, Pittsburgh, U.S.) [46]. These robots are all “hand-controlled semi-active robots”; the MAKO® and ROSA® using image technology but the NavioPFS® using only intra-operative anatomical and kinematic data. More recently, lightweight concepts such as the Mazor® (Mazor Robotics, Caesarea, Israel), used for minimally invasive spinal surgery [47], and the OMNIBotics™ (Omnirobotic, Massachusetts, U.S.) [48] system used for total knee replacements have arisen.

Impact of CAOS on general “orthopaedic forum”:

In June 2016, Dalton et al. published a very relevant article we would like to refer to as the common theme of this section [57]. Between 1980 and 2014, the authors examined patents and papers in relation to knee surgery and sorted them into four clusters of innovations, which could be used to link patents and publications: Unicompartmental Knee Replacement (UKR), Patient Specific Instrumentation (PSI), Navigation and Robotics. Three of these are part of the CAOS technology "family". Since 2004, the ratio between patents and publications increased from approximately 1:10 in 2004 to almost 1:3 in 2014 showing industry-driven innovation on technology introduction in the field of knee arthroplasty. (Figure 2)

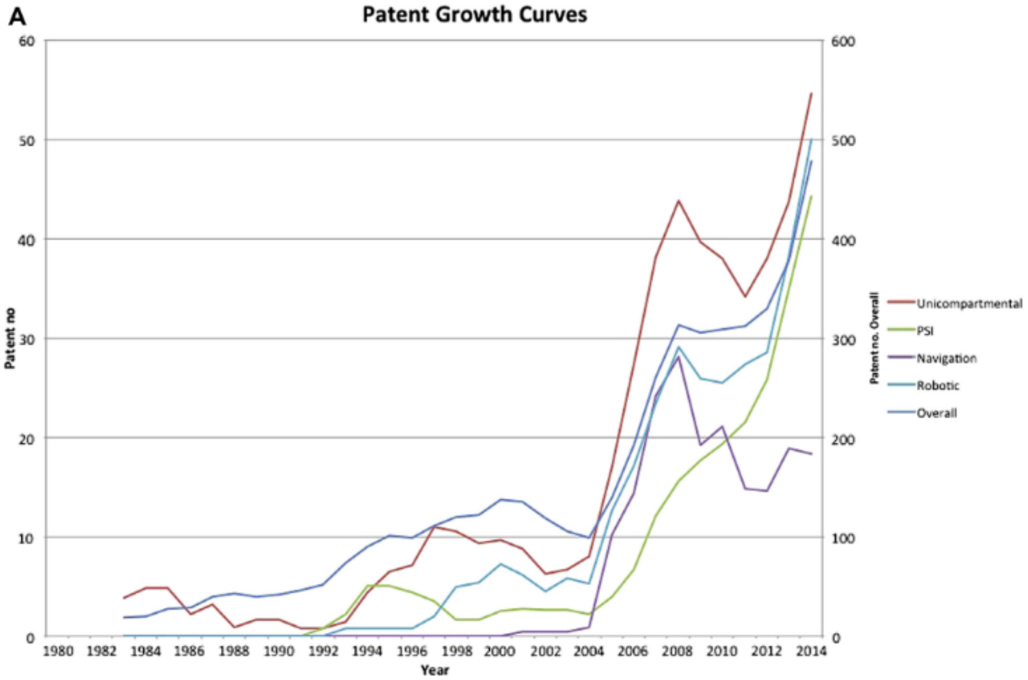

Figure 2: Graph of the normalized patent growth curve of the individual technology clusters and the overall knee arthroplasty patent curve. X axis referred to time between 1980 and 2014, Y axis referred to number of patents.

We investigated, along this chapter, the role of the industry in the introduction of any disruptive technology using the above quoted paper as a guideline and we also explore what may have been the role of CAOS in challenging some conventional surgical concepts.

Between 2001 and 2004, the number of publications regarding navigation multiplied by 20 (Figure 3). At the time, most of the large global multinational orthopaedic companies had little expertise with CAOS systems apart from Stryker and Medivision [8,58]. Most of the systems commercialised at the time were from smaller orthopaedic allied companies, e.g. Brainlab/ München, Germany; Aesculap/ BBraun Tuttlingen Germany; OrthoSoft, Montreal, Canada [59]

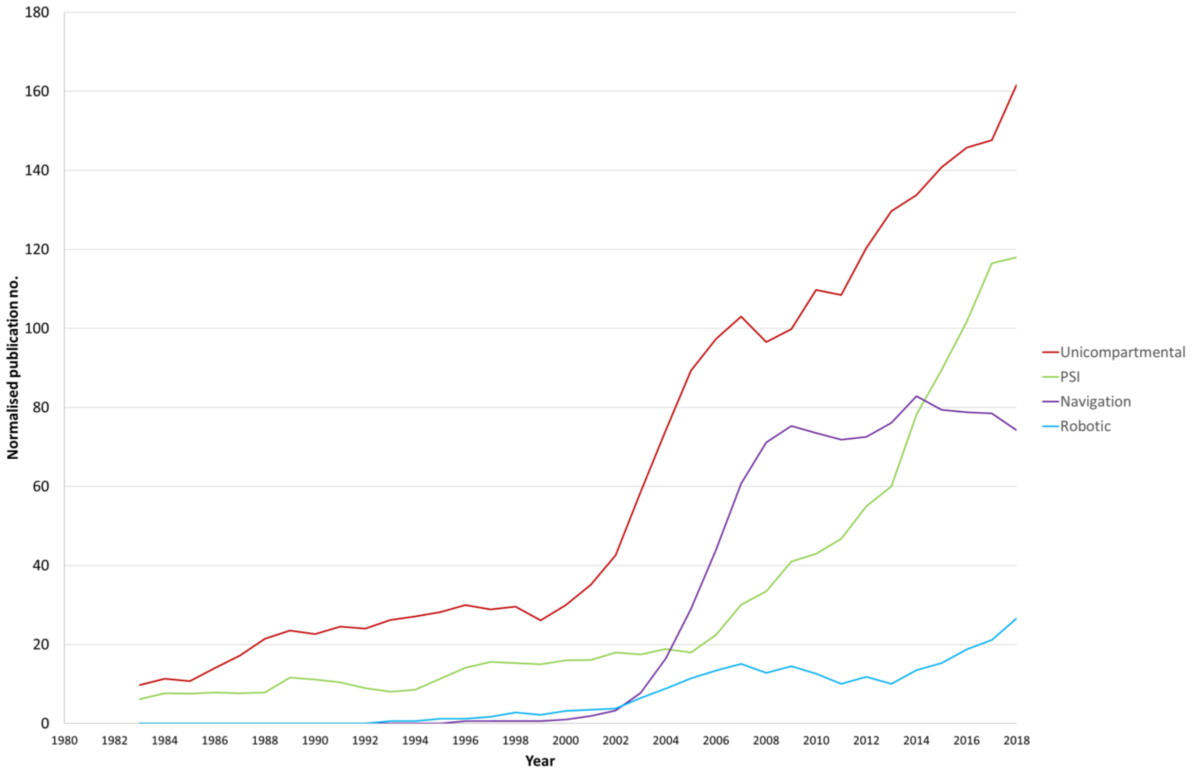

Figure 3: Graph of the normalized publication growth curve of the individual technology clusters and the overall knee arthroplasty publication curve. X axis referred to time between 1980 and 2014, Y axis referred to number of publications. Using the same methodology as Dalton et al. we reproduced their figures extending them to 2018.
Search terms in Pubmed were as Table I with date range set to 1980/01/01 to 2018/12/31. We also searched for papers on alignment with and without CAS (Table I). Publication numbers were normalised to 2014 using the following formula as per Dalton et al.

$$II_i^{normalised} = \frac{II_i^{original}}{c_i}$$

$$where\ c_i = \frac{t_i}{t_{2014}}$$

where II is the innovation index (number of patents or publications in area),i is year, t is total number of patents granted or paper published and c is the innovation constant. Data were then plotted using a 4-period moving average as per Dalton et al.

Whether this sudden interest in CAOS made the larger companies react vigorously or not is difficult to confirm due to their strategic secrecy. However, it is clear that from 2003 onwards [60] a wave a publications, supported by the large corporations, promoted Minimally Invasive Surgery (MIS) for both hip and knee arthroplasty [61,62], which created a temporary diversion from the adoption of CAOS technology [63].

In 2014, we published a paper examining the reasons why CAOS was not mainstream at the time, as opposed to laparoscopic surgery and neuro-stereotactic guided surgery as both of them are unchallenged methods in their field [59]. Many factors limited the spread of CAOS for wide adoption in total knee replacement (TKA), the object of our study, because of its perceived risks, additional surgical times and additional attendant costs [1]. Nonetheless, we found that two main factors limiting CAOS expansion were ergonomics and economics [59]. Zheng et al. confirmed the first factor in his recent review and wrote “that one of the barriers to adoption of navigation” comes from “intra-operative glitches, unreliable accuracy, frustration with intra-operative registration and line of sight issues” [5].

According to Dalton et al. between 2004 and 2008, the number of patents registered under the “knee replacement” or “knee arthroplasty” label by industry grew steeply (Figure 2). We could deduce from this, that the orthopaedic industry responded to the demand for CAOS and invested in new and better designed systems to match surgeons’ expectations. The number of publications rocketed during this period showing solid evidence of interest in the technology but also genuine vigilance from orthopaedic community in order to avoid worrying past experiences [64].

Ergonomic issues generated early scepticism in CAOS technology immediately after its introduction. Moreover, studies revealed fractures related to pin tracker fixation [65,66,67], infections on trackers sites [58,68] and lengthy surgery too [69]. Some early CAOS prototypes were probably launched too quickly, driven by the desire to be first, or the need to counteract competition. Without the correct support and training, these issues created fear in some of the early adopters [70]. However, later evidence did not confirm the initial impressions regarding the increase of complication rates but undoubtedly emphasised the increasing operative time due to the additional manipulations compared to conventional knee surgery [71].

Despite, in 2007, Novack concluding that CAOS navigation was potentially a cost-effective or cost-saving addition to TKA [73], economics was found to be one of the main issues limiting CAOS adoption, not only due to the high capital cost of the systems themselves, but also due to the overall overhead cost related to increased length of surgery [72] and increased operating expenses with regards to inventory and surgical assistances [59].

The number of patents dedicated to navigation after 2008 reduced, whereas more investment was directed towards on PSI and two years later towards robotic technologies [57] (Figure 2). Also by 2008, the number of publications for navigation declined whereas they increased for PSI [74,75]. It can be postulated, therefore, that the industry felt that investing more into PSI may, on the one hand, solve the ergonomic issues surgeons complained about but also, on the other hand, may solve their economic problems related to navigation.

The original claims for using CAOS, and specifically navigation, was that the technology would be more accurate and precise than conventional surgery, enhancing the three-dimensional position and alignment of joint replacements, spine screws or the safe bone/tissue resection in orthopaedic oncology [4]. While the evidence demonstrating the superiority of knee navigation over conventional instrumentation in accuracy and precision for alignment grew, some surgeons questioned the concept of alignment itself. It is difficult to identify what triggered this trend whether it is “safe vigilance reaction”, “backfire effect” or, “confirmation bias” amongst orthopaedic community and companies [71,76,77,78]. Dividing the number of papers published on knee alignment and TKA between 1976 and 2016 into those related to CAOS and those which are not, it seems clear to use that CAOS technology drove the discussion associated with knee replacement as far as alignment and balancing are concerned (Figure 4 and 5). Therefore, challenging the concept of alignment was maybe a natural evolution to the discussion?

After challenging the evidence on accuracy and precision of CAOS systems in knee arthroplasty navigation, a dispute also arose around the lack of evidence of patient functional improvements [79,80,81,82,83]. Siston et al. [71] had already argued in 2007 the lack of evidence in any kinematic knee improvement after CAOS knee replacements. The combination of a lack of strong evidence of functional improvements and controversies around alignment in knee arthroplasty potentially fuelled new technological concepts, such as the so-called kinematic alignment more popular after 2014 according to number of publication (Figure 3 and Figure 4). This may have suggested that accuracy and precision in knee replacement may not be paramount as we thought [84,85].

In the same vein, some argued about the lack of improvement of long-term implant survivorship in well-aligned knee replacements with or without navigation [86,87]. However, De Steiger et al. showed from Australian registry data that in 44,573 computer assisted primary TKAs (14.1% of total) there was a reduction in the overall rate of revision in patients less than 65 years old [88]. At the same time, new publications confirmed functional improvements after CAOS TKA. Rebal et al. showed that navigated TKAs had a higher increase in Knee Society Score at 3-months follow-up and at 12 months follow-up compared to conventional knee replacement [89].

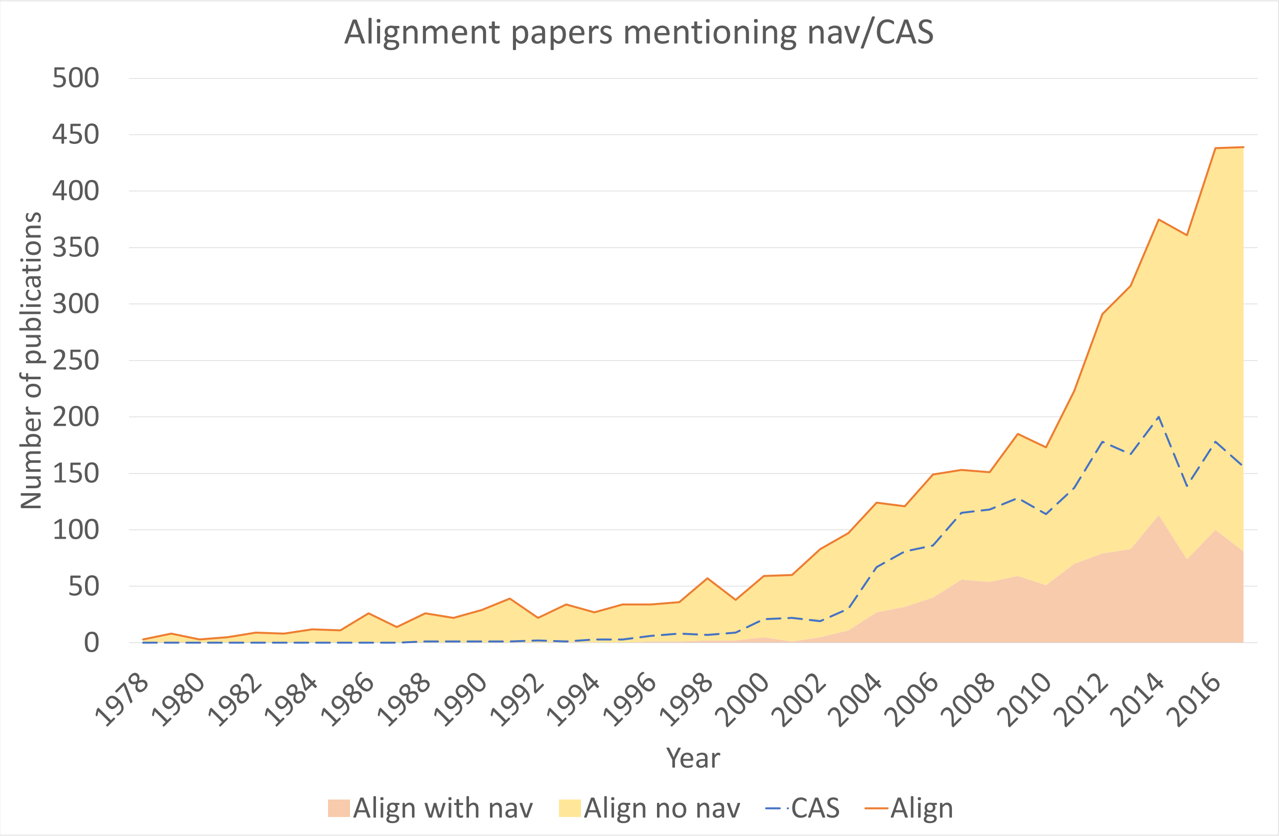

Figure 4: Query dividing alignment papers by those including nav and those excluding nav pubmed - ((((knee) AND (arthroplasty OR replacement)) AND (alignment OR balance OR balancing OR "soft-tissue"))) AND (navigation OR CAS OR "computer aided" OR "computer assisted") pubmed - ((((knee) AND (arthroplasty OR replacement)) AND (alignment OR balance OR balancing OR "soft-tissue"))) NOT (navigation OR CAS OR "computer aided" OR "computer assisted"). X referred to time (1978 to 2016) and Y referred to number of publications on Alignment with Nav and without.

As already mentioned, after 2010, the orthopaedic industry had invested heavily in robotic-assisted technology [90] despite the unsuccessful past market introduction [91,92,93], and less in navigation certainly to offset implant price reduction and the lack of instalments for the costly surgical trays/instruments [93]. Selling at a very high price, robots became suddenly appealing to the industry but on the other hand, high capital costs remained an obvious and significant restraining factor of in the use of this technology[95,96,97]. Investment grew more abruptly by 2012 onwards where industry tried to change the paradigm from computer aided technology to robotic aided technology [90]. The Mako® robot was one of the drivers of robotics in orthopaedics in reviving UKA market clearly noticeable on Dalton et al. figures with growing number of publications in UKA but also patents related to UKA [98].(Figure 2 and 3)

Mako® attracted Stryker®, one of the leading orthopaedic majors in the world leading to the acquisition of Mako® for $1.6 billion between 2012 and 2013 by Stryker, launching the “robot wars” between competitors. Smith & Nephew bought the Navio®/BlueBelt Technology for $275 million in 2016, Zimmer bought the ROSA® robotic system for at least $132 million, and more recently Johnson & Johnson invested in a new robot named Orthotaxy® for an undisclosed amount.

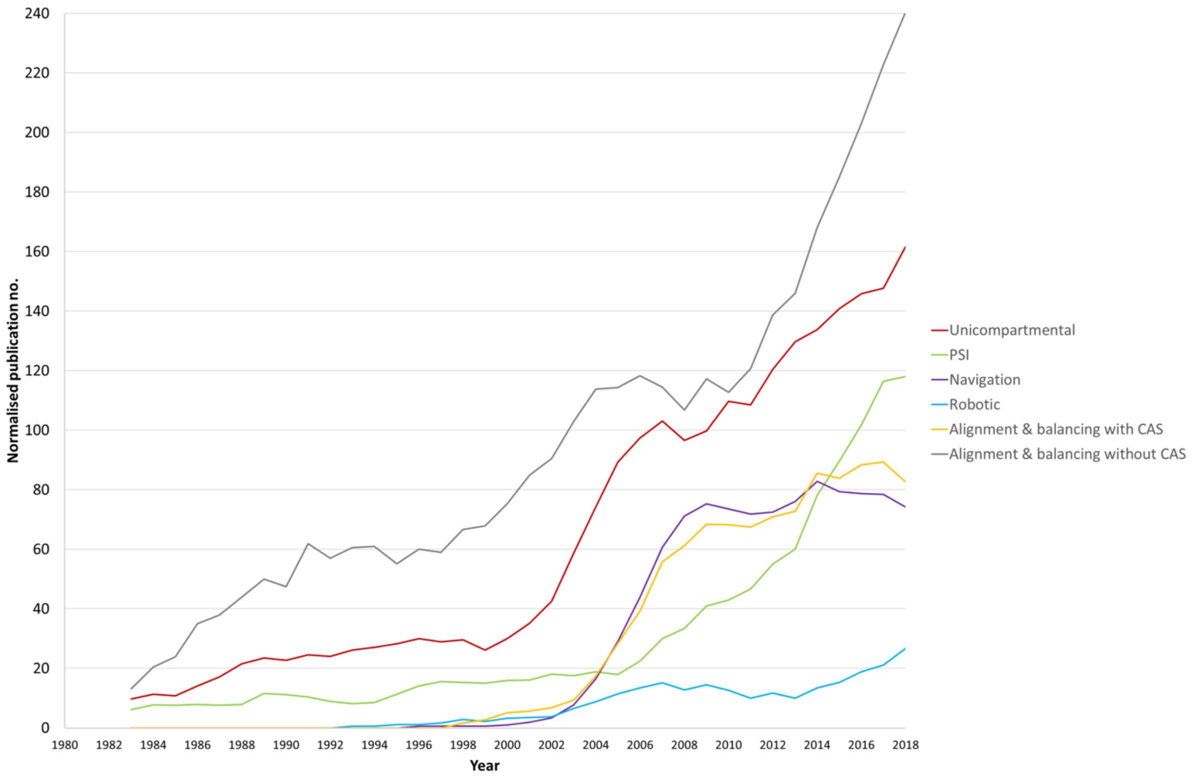

Figure 5: Relationship between alignment and balancing publications with CAS (yellow) and without (purple). The two line are almost overlapping until 2014 which coincidently coincide with the increase of publications related to robotics but also the spread so-called kinematic alignment concept.

After 2014, while the number of publications increased for PSI, navigation and robotic publication numbers went to opposite direction in favour of the later to the former. This would confirm our previous statement about the “robot-war” between companies.(Figure 4 and Figure 5)

Swank M. et al. suggested that capital cost of robotic knee arthroplasty maybe recovered in as few as two years if 50, 70, and 90 cases were performed in the first three years [97]. Moschetti et al. carried out a Markov analysis on UKA and showed that above 94 UKAs a year, robotic UKA is cost-effective [96]. All these studies speculated on significant better functional outcomes [51,99] and the potential reduction in revision [95].

In surgical fields other than arthroplasty, the additional accuracy afforded by navigation enhances patient safety and facilitates more complex surgery to be attempted. However, in joint replacement, the additional benefit of navigation resides purely in the accuracy and resulting alignment itself: the technology is being used to replicate conventional surgery, as opposed to opening up new surgical possibilities. Indeed, the MAKO® is now being used to perform THR – a highly successful conventional operation. Therefore, in essence, to have a wider adoption of CAOS in arthroplasty, surgeons must admit, individually and as a community, that their conventional arthroplasty surgery could be performed “better” with computer-assistance and with increased cost-effectiveness. Some surgeons hold this view, whilst others do not. This cognitive dissonance amongst many orthopaedic surgeons, which has made them sceptical about CAOS for some years, may generate a complex conundrum for the orthopaedic industry promoting robotic systems as more accurate and precise than navigation, since today’s robotic systems are only navigators with a robotic tool. To quote Cartiaux et al. “It is not yet possible to say unequivocally that improvements in the accuracy of the assisted surgical gestures substantially impact the outcomes of surgical procedures” [4]. However, there are surgeries in orthopaedics where the consensus is convincingly in favour of CAOS such as in oncology [100], spine applications [101] or complex cases in arthroplasty [102].

Future of CAOS

CAOS combines many sorts of technologies and each one of the components is evolving along its own path. For example, sensors used with devices like the “VERASENSE Knee System”, (Ortho sensors, Dania FL, USA.) are the result of sustainable technology coming from microelectronics [103,104]. There are today dozens of different sensors measuring PH, temperature, motion, speed, etc… all becoming smaller, being more efficient and more accurate [105]. This is how these nanotechnology or small sensors are now even used in some experimental surgical implants, like knee replacements. [106,107] The sensor is only an example of one technology that evolved on its own all over the years for the benefit of current or future CAOS systems.

We can divide the future of CAOS into four main categories:-

1. Improvement of image-guided surgery;
2. Navigation systems and peri-operative assessment devices;
3. Robotics and simulation;
4. Artificial intelligence, algorithms and simulation

1- Image-guided surgery.

Zheng and Nolte [108] reported a potential evolution in their paper published in 2015 with regards to a 2-D/3-D image stitching principle involving intra-operative C-arms, which could be used in spine surgery or trauma for long bone fractures. Combining MRI [109], CT data sets mainly used in spine surgery, as well as in oncology, will certainly benefit from this new technology. Statistical shape modelling [15,110] as great potential and it is true that the concept can be used with image-free technology, fluoroscopic images or even ultrasound tracking technology [14]. There is great potential to use all of those in joint reconstruction and revision in particular, but also complex primary joint replacements with severe deformities of large bone defects making difficult for surgeons to plan such abnormal anatomy. Therefore, a statistical model renders a better virtual anatomy construct to build up the missing parts. The other potential progress should come from the use of combined technology, such as EOS™ (EOS Imaging, Paris, France), which reduces considerably the radiation dose during joint x-ray assessment [111].

Hybrid CAOS systems are already under development and are able to combine all these image-guided tools, which will allow the surgeon to not only plan prior to surgery but also guide surgical intervention more accurately and, most importantly, more easily than today.

2- New generation of navigation systems and perioperative data measurements:

A number of smaller, smarter and easier to use systems exist, utilising tablets and small tracking devices, such as the BrainLab Dash®, (Munich Germany) [112], the

OrthoAlign (Orthoalign Inc, Ca, US) system [113] and the NaviSwiss (Naviswiss AG, Switzerland) intra-operative portable system [114]. New CAOS systems using sensors such as accelerometers such as eLIBRA [115]. Navigation-based technology using Infra-Red (IR) (PhysioPilot® Surgiconcept Ltd, UK) for perioperative kinematic knee measurements[116], accelerometers (BPM Pathway® UK), Electronic goniometers (product names), Ultrasound tracking system [117]

These devices generate huge amount of data potentially correlating perioperative to intraoperative measurements and will help to understand phenomena currently beyond our perception.

3- Robotic and simulation devices.

A new generation of robotic-assisted surgical tools will be able to use complex data to execute better planning. Today, robotic technology is just performing our current knowledge of conventional surgery. For instance, there are still controversies on what defines the best indications for UKA or what is the best alignment for TKA. It is thought that robotics can "reduce inventory, eliminate surgical trays, improve workflow and surgical efficiency and show net cost neutrality" [94]. Furthermore, as market-driven evolution has meant CAOS only replicates current surgical techniques, the potential exists for CAOS to inspire surgeon-led innovation to develop new types of surgery, not possible with conventional tooling. For example, implant design and CAOS systems have not been co-developed, losing the potential for smaller, bone-sparing prostheses. Ultimately, lesion-specific, biofabricated, mini-implants, replacing only the damaged tissue with new tissue, may be the final goal of arthroplasty surgery.

4- Artificial Intelligence, Algorithms and simulation.

The volume of collected data will increase considerably and will enable a new understanding of patterns in joint kinematics and certainly will give the new generation of navigation planning. CAOS is still at the stage of "measuring data" without really knowing what the best use of these data is. Artificial intelligence applied to big data analysis will draw clearer guideline pathways for professionals working in locomotor pathology and will provide surgical recommendations helping surgeons to perform more reproducibly and more accurately individual solutions for specific patients. Big data analyses combining peri- and intraoperative measurements of implant alignment/position, functional outcomes, satisfaction, long-term durability and so forth will shed light on the best course of action. Today we are still relying on crude information and data, even with the use of CAOS which may still explain some reticence against it.

Conclusion:

Computer Assisted Orthopaedic Surgery is no longer new. Several systems have been available for more than 20 years. Current systems and particularly the navigation systems are implementing mature technology whereas new robotic systems are using more advanced equipment which still requires assessments especially for those more recently launched on the market.

The original premises of the technology to make any surgery more accurate, more precise and reproducible in any circumstances aiming to improve patient's functional outcomes and long-term results have not been not fully proven. Despite vast amounts of evidence supporting the use of the technology, CAOS is still not mainstream. There are many reasons behind this slow uptake amongst the orthopaedic community which combine safe vigilance of surgeons, lack of strong evidence for long term benefits, additional cost of systems not offset by any third parties and mostly industry driven recommendation of practices.

The industry is still looking for the best model to put into operation: computer assisted technology or robotic assisted technology as it is referred today either for semantic or marketing reasons. Technology will find its place in orthopaedics once the commercial model is stable and comprehended enough by all parties involved in patient care. It took many years for endoscopy and arthroscopy in orthopaedics to become an undisputed technology in the field. In the later years, industry, health providers, practitioners and patients all claimed superiority of the pros with respect to the cons of this technology in routine practice. This has not happened in the field of CAOS yet.

According to BCC Research, the global surgical robotics and computer-assisted surgery market reached nearly $3.5 billion in 2015. [118] This market is expected to increase from $4.0 billion in 2016 to $6.8 billion in 2021 at a compound annual growth rate (CAGR) of 11.3% for 2016-2021. [118] Undoubtedly, CAOS will expand over the coming years even though patients and even clinicians will still need to find their way into true information circulating on the web [119] and relevant evidence.

Indeed, CAOS is a broad family covering any technology from preoperative computer aided planning, intraoperative robotic assistance to postoperative computer measurements and therefore it includes under its umbrella many different systems and technology which don’t have the same qualities.

In this paper, we reviewed some of key features of the past of CAOS, looked at the current “state of the art” and imagine some of the future options for CAOS that readers will encounter in coming years. We hope that this review will help provide a clearer perspective on this rather cluttered subject.

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