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Application of robotics in orthopaedic surgery

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Abstract
In recent years, with emerging technologies, robots are widely used in all possible fields due to their high precision and repeatability especially during procedures which require fine movements beyond human control. Over the decades medical robots have gained acceptance in many surgical procedures for locating lesions accurately and assisting the surgeons in holding and fixing the instruments. Robotic surgery although is advancing exponentially but is still in its infancy and has unlimited potential in the future of orthopaedics and trauma.

Keywords: Computer assisted orthopaedic surgery, orthopaedics, virtual modelling, registration, navigator

Introduction
In recent years, with emerging technologies, robots are widely used in all possible fields due to their high precision and repeatability especially during procedures which require fine movements beyond human control [1, 2]. Its influence on the surgical field in which surgeries are planned, simulated and performed are also evolving [3]. Decades of exponential advancement, medical robots have gained acceptance in many surgical procedures for locating lesions accurately and assisting the surgeons in holding and fixing the instruments [4, 5].

Although this technology have been used in surgical field since the mid 1980's still the use of robotics in orthopaedics is still in infancy [2] Robot assisted orthopaedic surgery was first performed in California in 1992 where a total hip arthroplasty was done using the ROBODOC system [2, 6].

Computer assisted orthopaedic surgery (CAOS) is the unison of processing units, robotic technology, human judgement and skills to perform the task better than either could do individually [7, 8].

Steps in robot-assisted surgery
Virtual modelling
First and the foremost step involves the mapping of patient's anatomy. Surgery plan is later decided based on the virtual model. There are various methods of virtual modelling.

Pre-operative image modelling are done with the help of mostly CT scans as it has excellent soft tissue-bone contrast and no geometrical distortion.[9] Intra-operative imaging modalities were introduced due to the limitations of pre-operative virtual modelling where there might be a change in the bony arrangement from the time of image acquisition to time of surgery. As a consequence, the virtual model may vary leading to unpredictable inaccuracies during the navigation or robotic procedures. To circumvent this obstacle intra-operative CT scanning was proposed [10] but this method is not ideal as it requires infrastructural changes which often require tremendous renovation of the hospital's facility. This in turn led to the development of fluoroscopy-based navigation system [11, 12, 13]. This system is superior to the previous systems as this device combines 3D imaging with intra-operative data acquisition and is evolving continuously.

The final navigation system does not involve any radiological images for virtual modelling. This system is known as Surgeon defined anatomy (SDA) which acquires graphical representation of the anatomy by intra-operative digitization. This navigation system is most commonly used in soft tissue structures [14].

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Registration
Navigation system and the pre-operative plan perform automated actions which are usually expressed in the local coordinate system of the virtual model. More often than not this local coordinate system is different from the one in which navigator operates intra-operatively. In order to overcome the differences, mathematical relationships between both coordinate spaces need to be optimized. When pre-operative images are used for virtual modelling, this step is performed interactively by the surgeon during registration, this process is also known a matching [15].

Various methodologies have established different techniques of registration. These methods to compute registration transformation are pair point matching, surface matching [16], rigid fiducial markers which requires additional surgical implantation [17], calibrated fluoroscopic images, calibrated ultrasound images [15] and intra-operative A-mode ultrasound probe base digitization [18, 19]. In intra-operative virtual modelling registration is an intrinsic process. As the device position along with the image calibration process automatically determine the spatial relationship between the virtual model and position of the patient at the time of surgery. This in turn is better than the matching done by the surgeon in case of pre-operative image model.

Another alternate is the employment of individualized custom templates based on patients specific 3d bone model from pre-operative 3d data. This method was introduced by Radermacher et al. [20]

Navigator
Registration relates the optimized plan and pre-operative images with the position of the patient during surgery. The navigator is a device that provides a global, three-dimensional coordinate system in which the target is to be treated and the current location and orientation of the utilized end-effectors are mathematically expressed [9].

Robots are the navigator themselves in this type of computer assisted orthopaedic surgery. The end effectors of robots are programmed to carry out specific tasks. Depending upon the level of autonomy of these devices, the actions performed and guidance required by surgeons, these systems are classified into active, passive or semi-active [21, 22, 23].

Active systems conduct a specific task autonomously under the watchful eyes of a surgeon without any additional support. Passive system perform no action autonomously, their main role is providing a surgeon with additional information pre and intra operatively.

Semi-active or templating system's actions are restricted to course a predefined surgical strategy, where outcome still depends on the manoeuvres performed by the surgeon.

Another component of navigator are trackers. It is a spatial position tracking device where it tracks the bony structures with respect to the location of the surgical tools and how they orient themselves during the surgical procedures. The most common tracker devices are optical trackers using light emitting diodes or light reflecting spheres or plates [24, 25]. The drawback of optical tracking require a direct line of sight during the surgical procedure.

Other types of tracking devices make use of magnetic or acoustic sensors, most recent of them being inertial measurement unit (IMU) [26-32].

These exponential development of intra-operative sensors and tools and convenient computer interface, provides unlimited potential for definitive surgical outcomes. This article is designed to provide the current scenario and the future of the computer assisted orthopaedic surgery.

Application of computer assisted orthopaedic surgery
Total knee arthroplasty (TKA)
Recent studies in TKA have shown that robots are effective in regaining mechanical axis in knee replacements without damaging much of the adjacent structures, improves implant positioning and reduces complications associated with conventional surgeries.

Khoplas A et al. [33] (2017) conducted the cadaveric study to assist the integrity of the various soft tissue structure of the knee and the requirement of tibial subluxation and patellar eversion during robotic arm assisted TKA. In this study robotic arm assisted TKA was done for 6 cadaveric knees and compared to 7 control cases were TKA was done manually. The mean Kellgren Lawrence score was 2.8 in robotic arm assisted TKA and 2.6 in the control and the soft tissue damage were evaluated visually by an experienced surgeon. The degree of tibial subluxation and patellar eversion were also noted. This study revealed in robotic arm assisted TKA there was no visible evidence of disruption of soft tissue structures.

Yang et al. [34] (2017) compared the clinical results and radiological results between conventional TKA and robotic TKA using ROBODOC system, which is an active system, with cruciate retaining implant. A total of 113 primary TKAs were retrospectively reviewed of which 42 were conventional TKAs and 71 were robotic TKAs. Both groups had similar clinical outcomes as well as long term survival rates but the robotic TKA group had markedly fewer post-operative leg alignment outliers and fewer radiolucent lines.

Kyu-Jin et al. (2018) [35] evaluated 351 patients of which 155 patients underwent robotic TKA using ROBODOC system and 196 patients underwent conventional TKA. All clinical evaluation resulted in significant improvement in both groups. Higher number of outliners were seen in conventional TKA groups. The cumulative survival rate in robotic TKA were found to be 0.3% more than conventional TKA (p= 0.563).

Kim YH et al. [36] (2020) conducted a randomized controlled trial on 1406 patients of which 700 patients underwent robotic assisted TKA and 706 patients conventional TKA with a minimum follow up of 10 years. This research concluded with no difference between conventional TKA and robotic assisted TKA with respect to overall survival rate, functional outcome score, aseptic loosening and complications.

Unicompartmental knee arthroplasty (UKA)
Unicompartmental knee arthroplasty is a unique surgical procedure which is in demand as it has numerous advantages over TKA such as decrease collateral injury to the soft tissue during surgery, improved kinematics and rapid rehabilitation [37].

Keene et al. [38] (2006) conducted a study in limb alignment is computer assisted minimally invasive UKA, where 20 patients underwent bilateral medial compartmental knee arthroplasty, results showed that computer assisted UKA yielded significantly improved alignment post-operatively compared to conventional bilateral simultaneous arthroplasty. Improved alignment is associated with better clinical outcomes.

Cobb et al. [39] (2006) performed a study of acrobot systems in UKA which was prospective randomised controlled trial, in which UKA was done on 28 knees and were randomly segregated into two groups based on robot assisted UKA and conventional UKA. The group operated with robot assisted UKA had better tibio-femoral alignment and better functional

clinical outcomes compared to the conventional UKA. This study implies the reliability and the reproducibility of a pre-operative plan using acrobat devices.

Lonner et al. [40] (2010) conducted a study to determine the improved tibial component alignment using robot arm assisted UKA where 31 knees underwent robot arm assisted UKA and 27 knees were underwent conventional UKA by comparing radiologically the pre-operative planned position of the tibial component were compared to the post-operative radiograph alignment to evaluate the error of bone preparation and variance with each technique. This study along with several others has emphasised the accuracy of robot arm assisted UKA is better than conventional method with respect to tibial slope and varus-valgus alignment [40-43].

Pearle et al. [44] (2017), a prospective multicentric study was performed to assess the clinical outcomes, survivorship and satisfaction rate. 1135 knees were operated using robotic assisted medial UKA and the patients were for followed up for a minimum period of two years. Study concluded with higher survivorship and satisfaction rate post robot assisted UKA at short term follow up. Recently several other studies have shown that patient treated with robot assisted UKA allows for precise planning, have improved alignment, superior functional outcome, shorter hospital stay and rehabilitation [42, 45-51].

Total hip arthroplasty (THA)
For the past 20 years robots have been used in the surgical field for THA. In the year 1992 ROBODOC was introduced (integrated surgical system, Davis, California) to improve surgical outcome in uncemented THA [52]. Robot assisted THA is gaining popularity and has become a common method for implantation as it has better pre-operative planning and accurate intra-operative procedures which results in decreased limb length discrepancy and improved varus-valgus orientation [53]. Nishihara et al. [54] (2006) compared hand rasping and robot milling for stem implantation in cementless THA and were evaluated based on clinical and radiological results, significant superior Merle D' Aubigne hip score were seen in robot milling group and there were no intra-operative femoral fractures, implant fit were superior radiologically whereas rasping are more prone for iatrogenic femoral fractures, undersizing of the stem and inferior implant fit due to high vertical seating and unexpected femoral anteversion. Similar studies done by Nakamura et al. [55] and Domb et al. [56] showed that robotic THA had precise implant positioning, less limb length discrepancy and also reduces stress shielding in proximal femur. Lim et al. [57] further compared implant positioning and primary stability in short metaphyseal-fitting stem implant, robot assisted group had better alignment and implant seating.

Although previous studies implied better implant alignment and fit using robotic system long term studies had not been done until Bargar et al. [58] (2018), conducted a long term study for a mean follow up of 14 years showed no stem loosening complications and better clinical outcome.

Spine
Computer assisted orthopaedic surgery is also extensively used in spine surgeries for precise positioning of pedicle screw in minimally invasive spinal fusion this technique also has comparatively less radiational exposure(3.5 vs 13.3 sec/screw [$p<0.001$]) and shorter duration of hospital stay compared to free hand technique [59, 60].

Trauma
A semi-automated telemanipulation machine surgical technique which is known as Trauma Pod is in its developmental stage to treat critically injured patients on the battlefield [61]. Robots also help in accurately reducing fractures using navigation system. Percutaneous joint fracture reduction was accomplished in about 3 minutes through image guided surgical robot systems [62-64]. CAOS has also been used in intramedullary nailing for identification of entry points and locking distal screws [65, 66]. The da Vinci system has been used to efficiently repair brachial plexus injury with reduced collateral damage [67, 68].

Conclusion
Robotic surgery although is advancing exponentially but is still in its infancy and has unlimited potential in the future of orthopaedics and trauma. Surgeons can decrease the steepness of the learning curve and increase their proficiency by training on cadavers or simulation systems. Recent literature suggests CAOS helps the surgeon to better predict and influence surgical outcomes and is also much safer for the patients throughout. Further study of CAOS is needed to determine their expanded indications, and only the orthopaedic surgeon recognises the applications, goals and drawbacks of these systems to provide the best possible care.

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