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Research on artificial intelligence in shoulder and elbow surgery is increasing

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Background: Total health care spending in the United States is increasing. In order to improve our delivery of high-quality, patient-centric, and cost-effective care, artificial intelligence (AI) and its subsets are being increasingly explored and utilized in medicine. Applications of AI in orthopedic surgery, including shoulder and elbow surgery, are being actively studied and have stirred much discussion. However, the trends of research on AI applications in shoulder and elbow surgery have not yet been quantified. Thus, the purpose of this study is to explore the general trends of research in applying AI to shoulder and elbow surgery and to examine characteristics of these research publications.

Methods: A literature search was conducted using PubMed for all articles published between January 1, 2000 and May 12, 2022. The primary search query used was as follows: (shoulder) and (AI OR machine learning OR deep learning OR neural networks). Exclusion criteria were as follows: (1) not pertinent to orthopedic surgeons (2) not pertaining to shoulder or elbow surgery, and (3) not pertaining to AI, machine learning, and deep learning. Selected articles in high-impact and relevant orthopedic journals were further characterized and analyzed.

Results: The annual number of articles increased from 1 article in 2006 to 24 articles in 2021. There was a 4-fold increase in publications between 2019 and 2021, and a 6-fold increase between 2018 and 2021. The average number of publications per year increased exponentially from 2010 to 2021 ($R2 = 0.608$; $P = .003$). The three journals with the most publications were *Journal of Shoulder and Elbow Surgery* (12), followed by *Arthroscopy* (2), and *Clinical Orthopaedics and Related Research* (2).

Conclusion: This study provides quantitative evidence for the first time that publications applying AI and its subsets to shoulder and elbow surgery are growing exponentially since the year 2010, with the most rapid growth beginning between the years of 2019 and 2020.

Total health care spending in the United States increased from an estimated $1.4 trillion in 1996 ($5259 per person) to $3.1 trillion in 2016 ($9655 per person), and it has now reached $4.1 trillion in 2020.[8,13] Such economic burden on patients and the system has driven an increased demand for high-quality, patient-centric, and cost-effective research and care. In order to improve various facets of the health care system, clinical applications of artificial intelligence (AI) and its subsets including machine learning (ML) and deep learning (DL) have been of interest. Several articles have highlighted and explained the principles of AI.[3,14,27,28] Concisely, AI involves simulating human intelligence using technology. Algorithms can be trained and applied for many different purposes; a few examples include automating diagnosis of pathologies from magnetic resonance imaging images, predicting patient outcomes after surgery, and assisting in clinical examinations during telehealth visits.

Applications of AI in orthopedic surgery are being actively studied in many subspecialties, including hip, knee, and spine surgery. In the hip literature, Rouzrokh et al developed and tested AI models for automated measurements of acetabular component inclination and version on radiographs following total hip arthroplasty.[35] In the knee literature, a recent study developed AI algorithms that performed well in predicting patients most likely to have a prolonged length of stay following revision total knee arthroplasty.[20] In the spine literature, Rudisill et al developed and validated an AI model for predicting early-onset adjacent segment degeneration following anterior cervical discectomy and fusion using demographic, clinical, and radiographic variables.[36]

Ethical approval for this study was waived by the institutional review board.

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Likewise, several studies applying AI to shoulder surgery have been published.[4,7,21,22,25,29,32] In one study, using a set of 21,544 elective total shoulder arthroplasty (TSA) cases, AI models were developed and performed well in predicting nonhome discharge and the occurrence of 1 or more postoperative complications following elective TSA.[25] Similarly, AI models were developed and performed well in predicting patient satisfaction two years after primary anatomic and reverse TSA patients.[32] These and other related investigations into the applications of AI in shoulder surgery have stirred much discussion. However, the trends on research in this area have not yet been quantified. Understanding the trends and details of publications in this area is helpful for characterizing academic interest in this area and for allowing the orthopedic community to identify journals and institutions of interest for research and training. Thus, the purpose of this study is to explore the general trends of research applying AI to shoulder and elbow surgery and to examine characteristics of these research publications.

Methods

A literature search was conducted using PubMed for all articles published between January 1, 2000 and May 12, 2022. The primary search query used was as follows: (shoulder) and (AI OR ML OR DL OR neural networks). All titles, abstracts, and full-text articles were screened. Additional pertinent studies were also identified through evaluating the reference lists of the articles from the keyword search and additional search queries using keywords such as "rotator cuff" and others. Studies of all levels of evidence were included.

Exclusion criteria were as follows: (1) not pertinent to orthopedic surgeons, (2) not pertaining to shoulder or elbow surgery, and (3) not pertaining to AI, ML, or DL. Of the final articles selected, those in high-impact and/or relevant orthopedic journals underwent additional evaluation and characterization. These journals included *Journal of Shoulder and Elbow Surgery (JSES), International, Journal of Shoulder and Elbow Arthroplasty, Orthopaedic Journal of Sports Medicine, American Journal of Sports Medicine, Arthroscopy, Journal of the American Academy of Orthopaedic Surgeons, Clinical Orthopaedics and Related Research), Acta Orthopaedica, The Journal of Bone & Joint Surgery,* and *Journal of Bone & Joint Surgery Open Access*. Further analyses included country of first author, institutional affiliation of first author, and citation count. Citation count was determined using Scopus as consistent with previous studies.[1,5,9,16] For most accurate trend analyses, only completed calendar years were used in analyses. A *P* value equal to or less than 0.05 was significant. All statistical and other analyses were performed using Microsoft Excel and SPSS Statistics (v28, 2021; IBM, Armonk, NY, USA).

Results

The primary search query using PubMed resulted in a total of 615 results. After identifying articles that met exclusion criteria, 79 articles remained. After evaluating reference lists and other relevant literature, 6 additional results were added for a total of 85. The annual number of articles increased from 1 article in 2006 to 24 articles in 2021 (Table I) (Fig. 1). The earliest publication included was in the year 2006. In the three most recently completed calendar years, 2021 had 24 publications, 2020 had 22 publications, and 2019 had 6 publications. There was a 4-fold increase in publications between 2019 and 2021, and a 6-fold increase between 2018 and 2021. The largest difference between any two consecutive years was between 2019 and 2020 with a difference of 16 publications. The average number of publications per year increased exponentially from 2010 to 2021 ($R^2 = 0.608$; $P = .003$).

Table I
Number of artificial intelligence publications in shoulder and elbow surgery by y.

Y	Number of publications for all	Number of publications for select journals
2022	20	3
2021	24	11
2020	22	6
2019	6	2
2018	4	2
2017	1	0
2016	4	0
2015	1	0
2014	1	0
2013	0	0
2012	1	0
2011	0	0
2010	0	0
2006	1	0

When analyzing only the high-impact and/or relevant orthopedic journals, there were 24 total publications (Table II). Of the 24 publications, 16 focused on shoulder arthroplasty, 0 focused on elbow arthroplasty, 1 focused on proximal humerus fractures, 1 focused on anterior shoulder instability, and 6 were miscellaneous. The earliest year was 2018 with 2 publications and the last completed calendar year was 2021 with 11 publications (Table I). The total publications per year increased more than 5-fold from 2 in 2018 to 11 in 2021. The three journals with the most publications were *JSES* (12), followed by *Arthroscopy* (2), and *Clinical Orthopaedics and Related Research* (2) (Table II). The most common country for the first author's affiliation was the United States of America (20). The two most common first author institution affiliations were Atrium Health Wake Forest Baptist Health/Wake Forest School of Medicine (4) and Cleveland Clinic (2). The most cited article (127 times) was published by Chung et al and titled "Automated detection and classification of the proximal humerus fracture by using deep learning algorithm" in *Acta Orthopaedica*.[6] The next two most cited articles were by Gowd et al in *JSES* (18 times) and Biron et al in *Journal of the American Academy of Orthopaedic Surgeons* (18 times).[4,11]

Discussion

AI and its subsets are being investigated for their applications and utility in orthopedic surgery, including total joint arthroplasty, spine surgery, and shoulder and elbow surgery. In shoulder and elbow surgery, advancements are being made in applying AI for predicting patient complications, predicting functional outcomes, assisting in evaluating rotator cuff tears from imaging, and more. However, no study has yet provided quantitative data on the trends and characteristics of publications on applying AI to shoulder and elbow surgery. This study provides quantitative evidence for the first time that publications applying AI and its subsets to shoulder and elbow surgery are growing exponentially since 2010, with the most rapid growth beginning between the years of 2019 and 2020.

The largest interval growth in publications happened from 6 publications in 2019 to 22 publications in 2020. Additionally, despite the literature search including less than half of the 2022 year (January 1-May 12), the number of publications found in 2022 was almost already equivalent to that of the completed year of 2021. Together, this data shows that the spark in interest and exponential growth in AI studies for shoulder and elbow surgery began recently in the past few years. The reason for this is likely multifactorial. First, with rising health care costs and disparities in

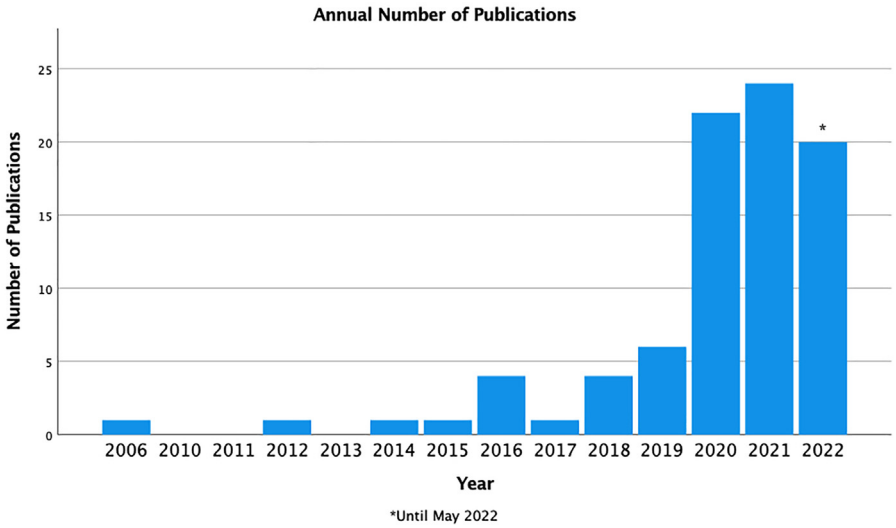

Figure 1 Annual number of publications in shoulder and elbow surgery.

Table II
Number of artificial intelligence publications in shoulder and elbow by journal.

Journal	Number of publications
JSES	12
JSES International	1
JSEA	1
Orthopaedic Journal of Sports Medicine	1
American Journal of Sports Medicine	1
Arthroscopy	2
Journal of the American Academy of Orthopaedic Surgeons	1
Clinical Orthopaedics and Related Research	2
Acta Orthopaedica	1
JBJS	1
JBJS Open Access	1

JSES, Journal of Shoulder and Elbow Surgery; *JSEA*, Journal of Shoulder and Elbow Arthroplasty; *JBJS*, Journal of Bone and Joint Surgery.

care, much attention has been brought to the importance of delivering high-quality, low-cost, and patient-centric care. With increasing promise of AI tools being able to assist in lowering costs and improving quality of care, researchers, physicians, and patients are becoming more aware of and interested in AI.[2,10,12,15,23,24,26,31] Second, the optimism and success seen in AI research and applications in other orthopedic subspecialties such as hip and knee arthroplasty and spine surgery has likely spurred more interest in shoulder and elbow AI research.[33,34,39] For example, Karnuta et al trained and externally validated a DL model to classify one of eight femoral-sided total hip arthroplasty implants directly from anteroposterior plain radiographs, which performed with a mean speed of 0.02 seconds per image, area under the curve (AUC) of 0.99, and accuracy of nearly 98%.[17] Third, although AI and its subsets have been around for several decades, technological advances such as faster computer processing speeds have allowed research in this area with big data to be more efficient and effective.[18,19,38]

To better understand which areas of AI applications are of most academic interest in shoulder and elbow surgery, the citation count for articles published in high-impact and/or relevant orthopedic journals was examined. The most cited article involved applying AI to assist with detecting and classifying proximal humerus fractures from plain anteroposterior shoulder radiographs. In this study by Chung et al, a deep convolutional neural network was developed and tested using 1891 images. The CNN performed excellently in distinguishing normal shoulders from proximal humerus fractures (0.996 AUC) and classifying fracture type (AUC 0.90-0.98). Importantly, when compared to general physicians, general orthopedists, or orthopedic shoulder specialists, the CNN often performed superiorly or similarly. As supported by the high citation count, this shows the great interest that orthopedic surgeons and other musculoskeletal investigators have in AI applications that assist in detecting and classifying shoulder and elbow pathology directly from images.

Similarly, the next two highest cited articles involved predicting patient complications and length of stay following TSA.[4,11] Gowd et al used a national database to train and validate several ML algorithms for predicting any adverse event, extended length of stay, surgical site infection, and more.[11] Biron et al also used a national database and developed a random forest model that performed well (AUC 0.77) in predicting patients with a short length of stay (1 day or less) following TSA.[4] The high citation count for both previously described articles shows the interest of orthopedic investigators in using AI for risk-stratification and prediction analyses.

This study is not without limitations. Only PubMed was used in this study, so it is possible that not all articles pertaining to AI applications in shoulder and elbow surgery were included. However, PubMed is one of the most used and robust biomedical search engines providing access to over 34 million, high-quality research citations and abstracts that are relevant to physicians.[30] Additionally, the citation counts from Scopus may not include all citations, as the counts are limited to only those journals index within Scopus. However, Scopus' coverage is broad as it contains over 25,000 peer-reviewed journals and has more than 83 million records.[37]

Conclusion

This study provided quantitative evidence for the first time that research and publications in applying AI to shoulder and elbow surgery are growing exponentially. Many different areas of application are being explored, including automated evaluation and classification of rotator cuff tears from images, identification of implants, predicting post complications and functional outcomes following shoulder arthroplasty. As this study found an exponential

growth in annual publications since 2010, it is likely that this area will continue to grow expansively for many years to come. Orthopedic surgeons should be aware of these trends as advancements in AI applications in shoulder and elbow surgery have the potential to change daily clinical and operative practice.

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References

1. Ahmad P, Vincent Abbott P, Khursheed Alam M, Ahmed Asif J. A bibliometric analysis of the top 50 most cited articles published in the Dental Traumatology. Dent Traumatol 2020;36:89-99. https://doi.org/10.1111/edt.12534.
2. Areia M, Mori Y, Correale L, Repici A, Bretthauer M, Sharma P, et al. Cost-effectiveness of artificial intelligence for screening colonoscopy: a modelling study. Lancet Digit Heal 2022;4:e436-44. https://doi.org/10.1016/S2589-7500(22)00042-5.
3. Bini SA. Artificial intelligence, machine learning, deep learning, and cognitive computing: what do these terms mean and how will they impact health care? J Arthroplasty 2018;33:2358-61. https://doi.org/10.1016/j.arth.2018.02.067.
4. Biron DR, Sinha I, Kleiner JE, Aluthge DP, Goodman AD, Sarkar IN, et al. A novel machine learning model developed to assist in patient selection for outpatient total shoulder arthroplasty. J Am Acad Orthop Surg 2020;28:e580-5. https://doi.org/10.5435/JAAOS-D-19-00395.
5. Chen S-H, Huang R-Y, Huang L-G, Weng P-W, Chung C-H, Cheng C-D, et al. A bibliometric analysis of top 100 most-cited articles in dentistry with author(s) affiliated with Taiwan institutes. J Chin Med Assoc 2021;84:799-807. https://doi.org/10.1097/JCMA.0000000000000573.
6. Chung SW, Han SS, Lee JW, Oh K-S, Kim NR, Yoon JP, et al. Automated detection and classification of the proximal humerus fracture by using deep learning algorithm. Acta Orthop 2018;89:468-73. https://doi.org/10.1080/17453674.2018.1453714.
7. Devana SK, Shah AA, Lee C, Gudapati V, Jensen AR, Cheung E, et al. Development of a machine learning algorithm for prediction of complications and unplanned readmission following reverse total shoulder arthroplasty. J Shoulder Elb Arthroplast 2021;5:24715492211038172. https://doi.org/10.1177/24715492211038172.
8. Dieleman JL, Cao J, Chapin A, Chen C, Li Z, Liu A, et al. US health care spending by payer and health condition, 1996-2016. JAMA 2020;323:863-84. https://doi.org/10.1001/jama.2020.0734.
9. Elarjani T, Almutairi OT, Alhussinan MA, Bafaquh M, Alturki AY. Bibliometric analysis of the top 100 most cited articles on the basilar artery. Surg Neurol Int 2020;11:307. https://doi.org/10.25259/SNI_424_2020.
10. Gao S, He L, Chen Y, Li D, Lai K. Public perception of artificial intelligence in medical care: content analysis of social media. J Med Internet Res 2020;22:e16649. https://doi.org/10.2196/16649.
11. Gowd AK, Agarwalla A, Amin NH, Romeo AA, Nicholson GP, Verma NN, et al. Construct validation of machine learning in the prediction of short-term postoperative complications following total shoulder arthroplasty. J Shoulder Elbow Surg 2019;28:e410-21. https://doi.org/10.1016/j.jse.2019.05.017.
12. Guo J, Li B. The application of medical artificial intelligence technology in rural areas of developing countries. Health Equity 2018;2:174-81. https://doi.org/10.1089/heq.2018.0037.
13. Hartman M, Martin AB, Washington B, Catlin A, Team TNHEA. National health care spending in 2020: growth driven by federal spending in response to the COVID-19 pandemic. Health Aff (Millwood) 2022;41:13-25. https://doi.org/10.1377/hlthaff.2021.01763.
14. Helm JM, Swiergosz AM, Haeberle HS, Karnuta JM, Schaffer JL, Krebs VE, et al. Machine learning and artificial intelligence: definitions, applications, and future directions. Curr Rev Musculoskelet Med 2020;13:69-76. https://doi.org/10.1007/s12178-020-09600-8.
15. Kacew AJ, Strohbehn GW, Saulsberry L, Laiteerapong N, Cipriani NA, Kather JN, et al. Artificial intelligence can cut costs while maintaining accuracy in colorectal cancer genotyping. Front Oncol 2021;11:630953. https://doi.org/10.3389/fonc.2021.630953.
16. Kambhampati SBS, Vaish A, Vaishya R, Patralekh MK. Trends of arthroscopy publications in PubMed and Scopus. Knee Surg Relat Res 2021;33:14. https://doi.org/10.1186/s43019-021-00096-1.
17. Karnuta JM, Murphy MP, Luu BC, Ryan MJ, Haeberle HS, Brown NM, et al. Artificial intelligence for automated implant identification in total hip arthroplasty: a multicenter external validation study exceeding two million plain radiographs. J Arthroplasty 2022. https://doi.org/10.1016/j.arth.2022.03.002.
18. Kaul V, Enslin S, Gross SA. History of artificial intelligence in medicine. Gastrointest Endosc 2020;92:807-12. https://doi.org/10.1016/j.gie.2020.06.040.
19. Khan FH, Pasha MA, Masud S. Advancements in microprocessor architecture for ubiquitous AI-an overview on history, evolution, and upcoming challenges in AI implementation. Micromachines (Basel) 2021;12:665. https://doi.org/10.3390/mi12060665.
20. Klemt C, Tirumala V, Barghi A, Cohen-Levy WB, Robinson MG, Kwon Y-M. Artificial intelligence algorithms accurately predict prolonged length of stay following revision total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 2022;30:2556-64. https://doi.org/10.1007/s00167-022-06894-8.
21. Kumar V, Roche C, Overman S, Simovitch R, Flurin P-H, Wright T, et al. What is the accuracy of three different machine learning techniques to predict clinical outcomes after shoulder arthroplasty? Clin Orthop Relat Res 2020;478:2351-63. https://doi.org/10.1097/CORR.0000000000001263.
22. Kumar V, Roche C, Overman S, Simovitch R, Flurin P-H, Wright T, et al. Using machine learning to predict clinical outcomes after shoulder arthroplasty with a minimal feature set. J Shoulder Elbow Surg 2021;30:e225-36. https://doi.org/10.1016/j.jse.2020.07.042.
23. Lee D, Yoon SN. Application of artificial intelligence-based technologies in the healthcare industry: opportunities and challenges. Int J Environ Res Public Health 2021;18:271. https://doi.org/10.3390/ijerph18010271.
24. Lee MS, Grabowski MM, Habboub G, Mroz TE. The impact of artificial intelligence on quality and safety. Glob Spine J 2020;10:99S-103S. https://doi.org/10.1177/2192568219878133.
25. Lopez CD, Constant M, Anderson MJJ, Confino JE, Heffernan JT, Jobin CM. Using machine learning methods to predict nonhome discharge after elective total shoulder arthroplasty. JSES Int 2021;5:692-8. https://doi.org/10.1016/j.jseint.2021.02.011.
26. Lovejoy CA, Arora A, Buch V, Dayan I. Key considerations for the use of artificial intelligence in healthcare and clinical research. Futur Healthc J 2022;9:75-8. https://doi.org/10.7861/fhj.2021-0128.
27. Makhni EC, Makhni S, Ramkumar PN. Artificial intelligence for the orthopaedic surgeon: an overview of potential benefits, limitations, and clinical applications. J Am Acad Orthop Surg 2021;29:235-43. https://doi.org/10.5435/JAAOS-D-20-00846.
28. Martin RK, Ley C, Pareek A, Groll A, Tischer T, Seil R. Artificial intelligence and machine learning: an introduction for orthopaedic surgeons. Knee Surg Sports Traumatol Arthrosc 2022;30:361-4. https://doi.org/10.1007/s00167-021-06741-2.
29. McLendon PB, Christmas KN, Simon P, Plummer OR, Hunt A, Ahmed AS, et al. Machine learning can predict level of improvement in shoulder arthroplasty. JB JS Open Access 2021;6:e20.00128. https://doi.org/10.2106/JBJS.OA.20.00128.
30. U.S. National Library of Medicine. PubMed. National Center for Biotechnology Information. Available at: https://pubmed.ncbi.nlm.nih.gov/. Accessed May 15, 2022.
31. Oh S, Kim JH, Choi S-W, Lee HJ, Hong J, Kwon SH. Physician confidence in artificial intelligence: an online mobile survey. J Med Internet Res 2019;21,e12422. https://doi.org/10.2196/12422.
32. Polce EM, Kunze KN, Fu MC, Garrigues GE, Forsythe B, Nicholson GP, et al. Development of supervised machine learning algorithms for prediction of satisfaction at 2 years following total shoulder arthroplasty. J Shoulder Elbow Surg 2021;30:e290-9. https://doi.org/10.1016/j.jse.2020.09.007.
33. Purnomo G, Yeo S-J, Liow MHL. Artificial intelligence in arthroplasty. Arthroplasty 2021;3:37. https://doi.org/10.1186/s42836-021-00095-3.
34. Rasouli JJ, Shao J, Neifert S, Gibbs WN, Habboub G, Steinmetz MP, et al. Artificial intelligence and robotics in spine surgery. Glob Spine J 2020;11:556-64. https://doi.org/10.1177/2192568220915718.
35. Rouzrokh P, Wyles CC, Philbrick KA, Ramazanian T, Weston AD, Cai JC, et al. A deep learning tool for automated radiographic measurement of acetabular component inclination and version after total hip arthroplasty. J Arthroplasty 2021;36:2510-2517.e6. https://doi.org/10.1016/j.arth.2021.02.026.
36. Rudisill SS, Hornung AL, Barajas JN, Bridge JJ, Mallow GM, Lopez W, et al. Artificial intelligence in predicting early-onset adjacent segment degeneration following anterior cervical discectomy and fusion. Eur Spine J 2022;31:2104-14. https://doi.org/10.1007/s00586-022-07238-3.
37. Scopus Content. Content - How Scopus Works - Scopus - | Elsevier solutions. Available at: https://www.elsevier.com/solutions/scopus/how-scopus-works/content. Accessed May 15, 2022.
38. Wang SY, Pershing S, Lee AY. Big data requirements for artificial intelligence. Curr Opin Ophthalmol 2020;31:318-23. https://doi.org/10.1097/ICU.0000000000000676.
39. Wirries A, Geiger F, Oberkircher L, Jabari S. An evolution gaining momentum-the growing role of artificial intelligence in the diagnosis and treatment of spinal diseases. Diagnostics (Basel) 2022;12:836. https://doi.org/10.3390/diagnostics12040836.