

# Investigation on the Mechanical Properties of Total Shoulder Implants

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## ABSTRACT

The shoulder is one of the most mobile and complex parts. Anatomic total shoulder arthroplasty is a treatment method for osteoarthritis, rheumatoid arthritis, or proximal humerus fractures. This treatment reduces stiffness and restores joint mobility, allowing for the return to daily activities. An anatomic total shoulder arthroplasty consists of the humerus and glenoid elements. In this method, the humeral and glenoid elements are replaced with metal and polyethylene elements. The humeral element is usually made of Co-Cr alloy or Ti. The glenoid is commonly made of ultra-high density polyethylene (UHMWPE). Due to its mechanical properties, the most common Ti alloy used in anatomic shoulder implants is Ti-6Al-4V (titanium-aluminum-vanadium). CoCrMo alloy, on the other hand, is more durable than Ti and less susceptible to wear and tear, making it more suitable for replacing parts of the shoulder. Ultra-high-density polyethylene (UHMWPE) is a common bearing material used, but it can wear out, leading to loosening of the implant. In this review article, informations about the material and mechanical properties of humeral and glenoid elements were given.

**Keywords:** Shoulder, anatomic total shoulder prosthesis, Ti-alloy, Co-Cr alloy, polyethylene

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## INTRODUCTION

Surgical interventions for shoulder injuries, similar to other fields within orthopedics and traumatology, originated from anatomical research conducted in the late 19th century, progressing with open surgical methods during the early 20th century. From the latter half of the 20th century onward, advancements in arthroscopic and prosthetic surgical techniques (including arthroplasty) significantly improved due to enhanced technological infrastructure and developments in implant technology (Iqbal et al., 2013; Randelli et al., 2016).

Shoulder arthroplasty has gained substantial popularity in recent years, becoming the third most frequently performed joint replacement procedure, following hip and knee arthroplasty (Lin et al., 2016). Since the 1800s, shoulder arthroplasty has served as an effective treatment for shoulder pain and dysfunction resulting from arthritis, with early pioneers such as Themistocles Gluck and Jules Emile Péan performing the first total shoulder arthroplasties (Flatow and Harrison, 2011).

Orthopedic implants are extensively utilized across various medical disciplines. Conditions such as osteoarthritis and rheumatoid arthritis can severely impair the structure and function of synovial joints, including the hip, knee, shoulder, and ankle. Pain originating in these load-bearing joints often becomes debilitating, thus requiring surgical intervention involving prosthetic replacements or artificial joint implants (Waizy et al., 2013).

An orthopedic implant refers to a biomedical device specifically engineered to recover or substitute the functional capability of a damaged bone, joint, or cartilage through the replacement of deteriorated anatomical structures. One of the most representative examples is total shoulder arthroplasty (TSA), in which the glenohumeral joint is replaced by an artificial prosthesis (Erickson et al., 2020; Verestiue et al., 2021). The prosthetic system generally comprises an adjustable-length humeral stem inserted into the humerus and a smooth metallic head that articulates within the glenoid cavity of the scapula (Razfar et al., 2016).

To enhance joint mobility and reduce discomfort, anatomic total shoulder arthroplasty (ATSA) replaces the articular surfaces of both the humeral head and the glenoid (Edmonds, 2016; Wodarek and Shields, 2021).

The humeral component of shoulder arthroplasty has evolved substantially over time. In the earliest patient series reported by Neer et al. in 1974, long-stem monoblock humeral implants were employed and fixed using bone cement (Neer, 1974). Subsequent generations shifted toward components that promoted osseointegration, although early

designs still offered limited ability to replicate the native humeral anatomy, particularly in terms of head size and neck geometry (Boileau et al., 2006; Sperling et al., 2000).

Later, third-generation modular systems were developed, granting surgeons the capacity to better reproduce patient-specific anatomy by utilizing stems with variable neck-shaft angles and offset humeral heads (Godeneche et al., 2002). The modern design trend favors short-stemmed, metaphyseal-fixation, and stemless implants, reflecting an ongoing effort to preserve bone stock and improve fixation, with most major manufacturers now offering such contemporary configurations (Harmer et al., 2016).

The glenoid component is often considered the weakest link in TSA due to the high incidence of glenoid loosening-related failures (Papadonikolakis and Matsen, 2014). At present, the gold standard for TSA involves the use of all-polyethylene glenoid components, with cementing techniques employed to ensure early implant stability (Killian et al., 2017; Lazarus et al., 2002; Throckmorton et al., 2019; Wirth et al., 2012). While this design ensures initial stability, symptomatic loosening of the glenoid component over time remains common and may necessitate revision surgery (Papadonikolakis and Matsen, 2014). Metal-backed components have demonstrated favorable results in hip and knee arthroplasty, using both cemented and press-fit methods, leading to the increased use of metal-backed glenoid components to address the long-term concerns associated with all-polyethylene components (Castagna et al., 2010; Fucentese et al., 2010).

Anatomic total shoulder arthroplasty (TSA) comprises two primary components: the humeral and the glenoid elements. The humeral part is generally fabricated from titanium or cobalt–chromium alloy, whereas the glenoid element is most commonly designed as a concave socket constructed from ultra-high molecular weight polyethylene (UHMWPE). The conventional technique for securing the glenoid component involves the application of bone cement; however, uncemented press-fit fixation is also widely utilized in clinical practice (De Wilde et al., 2013).

Over time, various glenoid components and fixation techniques have been explored. Cemented all-polyethylene glenoid components have shown the best long-term survival rates; however, new designs continue to evolve, aiming to enhance fixation and the durability of glenoid implants (Singh et al., 2011). Cementless fixation using metal-backed components is an alternative, though concerns about their use have emerged due to reports of higher revision rates compared to cemented components (Sharplin et al., 2020; Wallace et al., 1999). Currently, the use of fully metal-backed glenoid components is not recommended (AAOS, 2020).

## MATERIALS AND METHODS

A comprehensive literature review was performed using the PubMed, Web of Science, Google Scholar and Scopus databases to identify all relevant publications concerning total shoulder implants in orthopedics and related disciplines. The search utilized key terms such as “total shoulder implants,” “shoulder implant materials,” “mechanical properties of total shoulder implants,” and “classification of shoulder implants.” Titles and abstracts were screened, and studies unrelated to shoulder implants were excluded. In addition, the reference lists of the selected papers were examined to capture further relevant studies. The included articles were subsequently analyzed for qualitative synthesis.

### *Titanium Alloys*

Over recent decades, titanium alloys have garnered extensive attention owing to their excellent strength-to-weight ratio, low mass density, remarkable corrosion resistance, and outstanding biocompatibility. As a result, these materials have been widely employed across various fields, including the aerospace, chemical, and nuclear industries, as well as in the production of load-bearing biomedical implants (Tsai et al., 2019).

Although titanium is not a natural constituent of the human body and performs no known biological function (Pais et al., 1977), it is regarded as a biologically inert and non-toxic material, even when present in relatively high concentrations (Chen and Thouas, 2015).

Two key mechanical properties largely account for the success of titanium-based implant systems. The first is the elastic modulus, which defines the stiffness of a material. Despite the mismatch between the elastic modulus of titanium (approximately 103–120 GPa) and that of cortical bone (~10–30 GPa), titanium remains considerably less stiff than stainless steel (~200 GPa) or cobalt–chromium alloys (~210 GPa) (Quinn et al., 2020; Sarraf et al., 2022).

This discrepancy in stiffness can result in a phenomenon known as stress shielding, which may lead to bone resorption, implant loosening, and increased osteoclastic activity (Quinn et al., 2020).

When compared with stainless steel and cobalt-based alloys, titanium demonstrates superior biocompatibility due to its high degree of resistance to corrosion and chemical degradation (Kodama, 1989; Lemons et al., 1976).

Because of its advantageous mechanical behavior and biological compatibility, the most frequently used titanium alloy in orthopedic applications—including anatomic total shoulder arthroplasty (TSA)—is Ti-6Al-4V (titanium–aluminum–vanadium) (Saini et al., 2015). This material is classified as an  $\alpha$ - $\beta$  phase alloy, signifying that it contains both hexagonal close-packed ( $\alpha$ -phase) and body-centered cubic ( $\beta$ -phase) crystal structures (Saini et al., 2015). The alloy is produced by combining pure titanium with 6% aluminum and 4% vanadium by weight. Aluminum serves as an  $\alpha$ -phase stabilizer, enhancing strength while reducing overall density, whereas vanadium acts as a  $\beta$ -phase stabilizer, improving the alloy's ductility and toughness (Saini et al., 2015).

### ***Cobalt–Chromium (Co–Cr) Alloys***

Cobalt–chromium alloys consist primarily of cobalt (Co) and chromium (Cr), with additional elements including molybdenum (5–7%), iron (>0.75%), manganese and silicon (<1%), nickel (<0.5%), and trace quantities of carbon, phosphorus, nitrogen, sulfur, tungsten and boron (Martí, 2000).

Although Co–Cr alloys are more costly and time-intensive to manufacture compared with titanium or other alloys, they provide superior mechanical strength. However, the presence of nickel poses potential toxicity risks; wear and frictional motion of the implant may release metal ions into the body, occasionally leading to allergic or inflammatory reactions (Gessner et al., 2019; Vaicelyte et al., 2020).

The inclusion of chromium enhances corrosion resistance by forming a stable, protective chromium oxide layer on the surface while simultaneously improving mechanical strength. Molybdenum increases strength through solid-solution strengthening and further stabilizes this passive oxide layer. The hardness and wear resistance of Co–Cr–Mo alloys can be tailored by modifying the carbon content, as high-carbon alloys (0.2–0.4% C) promote the formation of chromium and molybdenum carbides (Baron et al., 2015; Ramírez-Vidaurre et al., 2009).

Among metals used in biomedical applications, Co–Cr alloys demonstrate the highest wear resistance, making them the preferred biomaterial for components exposed to friction and repetitive motion (Acharya et al., 2021). These alloys are widely employed in TSA systems, including early metal hemiarthroplasty designs introduced in 1951 and in the development of early total shoulder prostheses (Zilber, 2017).

The first shoulder prosthesis developed by Neer was fabricated from Co–Cr–Mo alloy, also known as Vitallium (Neer, 1955). Co–Cr–Mo is mechanically stronger and more wear-resistant than titanium, rendering it ideal for articulating surfaces. In contrast, titanium provides superior osseointegration and osteoconductive potential, making it suitable for humeral stem components (Mehta et al., 2020).

The superior strength and hardness of Co–Cr–Mo compared with Ti-6Al-4V are attributed to its face-centered cubic crystal structure, greater interfacial adhesion strength, work-hardening capability, and low stacking-fault energy (Goldberg and Gilbert, 2004).

### ***Ultra-High Molecular Weight Polyethylene (UHMWPE)***

Ultra-high molecular weight polyethylene (UHMWPE) represents a distinct variant of polyethylene characterized by its extremely high molecular weight. Similar to other forms of polyethylene, UHMWPE is a semicrystalline polymer composed of two interwoven phases: a crystalline phase made up of highly ordered lamellae, and an amorphous, disorganized phase that may contain a partially structured “all-trans” interfacial region. The polymer's molecular mass and microstructural configuration are critical factors influencing its physical, chemical, and mechanical behavior—particularly its exceptional wear and abrasion resistance (Bistolfi et al., 2021; Affatato et al., 2018; Bracco et al., 2017; Taddei et al., 2017).

Because of its outstanding durability, polyethylene has long served as a bearing surface in total shoulder arthroplasty (TSA). However, gradual material wear can occur over time, which may contribute to implant loosening. To mitigate this problem, modern implant designs have incorporated modifications such as cross-linking and vitamin E stabilization to enhance wear resistance and extend implant longevity (Leafblad et al., 2022; Mehta et al., 2020).

In recent years, pyrolytic carbon has been investigated as an alternative biomaterial for shoulder hemiarthroplasty. This material is thought to minimize glenoid wear by promoting fibrocartilage regeneration and facilitating bone remodeling. Early clinical studies have reported improved joint function and increased range of motion in patients receiving implants made from this material (Park et al., 2023).

Since the 1950s, UHMWPE has been the most widely used bearing material in total joint replacement procedures (Bracco et al., 2017). Its popularity stems from its favorable wear characteristics, long-term stability, and biological inertness (Kurtz, 2004). Despite these advantages, polyethylene wear, along with the resulting periprosthetic osteolysis and implant loosening, continues to be a clinical concern—especially among younger, more active, or obese individuals (Kurtz et al., 1999; Baker et al., 1999).

Bittredge et al. (2022) explored one of the fundamental issues in orthopedic implant design, namely stress shielding, within total shoulder prostheses. In their study, they created and optimized a cellular, lattice-structured implant aimed at controlling the stiffness of the humeral stem used in shoulder arthroplasty. Test specimens were manufactured from Ti-6Al-4V alloy using the laser powder bed fusion (LPBF) technique, and their mechanical performance was confirmed through compression testing. Finite element analysis (FEA) indicated Young's modulus values ranging from 2 to 13 GPa, closely approximating that of human bone. Experimental testing showed that the LPBF-produced Ti-6Al-4V lattice structure, with a strut length of 5 mm, diameter of 1 mm, and complete lattice infill, exhibited an elastic modulus of 11.8 GPa, a yield strength of 200 MPa, a hardness of 380 HV, a surface roughness of 9.3  $\mu\text{m}$ , and a surface area-to-volume ratio of 3.7  $\text{mm}^{-1}$ . These results suggest that the material's mechanical properties make it suitable for orthopedic implants that require bone-like rigidity and enhanced osseointegration potential (Bittredge et al., 2022).

Wang et al. (2005) examined the biomechanics of the glenohumeral joint both before and after total shoulder arthroplasty (TSA), comparing three different glenoid designs: nonconforming, conforming, and a hybrid configuration with a conforming center and nonconforming periphery. Using six fresh-frozen cadaveric shoulders with an average age of 43 years, the study found no statistically significant differences ( $p > 0.05$ ) among the models in terms of joint motion or contact behavior. Glenoid components featuring minor conformity mismatches most closely reproduced the kinematics of the native joint. These observations were consistent with previous finite element analyses, which indicated that partial conformity can reduce contact stresses compared to either fully conforming or nonconforming designs (Wang et al., 2005).

Chen et al. (2022) investigated the initial fixation strength of various stemless and stemmed humeral implant designs and examined how fixation strength correlates with bone mineral density (BMD). Among five different stem configurations, the Stemless-C design, which incorporates a central screw and rim-fit mechanism, demonstrated less micromotion under axial loading than the Stemless-B design, which features a central body with three fins. In specimens with low BMD, the 50 mm and 130 mm stemmed implants provided superior fixation compared to the hollow-fin stemless models (Chen et al., 2022).

Michel et al. (2021) assessed the biomechanical role of protective cerclage during stem insertion in revision shoulder arthroplasty. The study used 28 human cadaveric humeri to compare cerclage configurations involving steel wire and FiberTape materials. The findings revealed that applying a cerclage delayed fracture occurrence during stem impaction. FiberTape demonstrated comparable performance to steel wire, and the level of applied tension had no notable impact on mechanical stability. These results highlight the potential clinical benefits of using cerclage reinforcement—particularly in uncemented or calcar-dependent arthroplasty—to improve fixation integrity and rotational stability (Michel et al., 2021).

Ryan et al. (2023) performed a biomechanical study using synthetic humeri implanted with uncemented long-stem, short-stem, and stemless prosthetic components, which were subjected to torsional loading until failure. The research demonstrated that decreasing stem length resulted in reduced torsional strength and altered fracture patterns. Both stiffness and maximum torque were significantly greater in short- and long-stem implants than in stemless designs. These findings indicate that stemless implants offer lower torsional stability and may be more prone to failure in cases involving poor metaphyseal bone quality (Ryan et al., 2023).

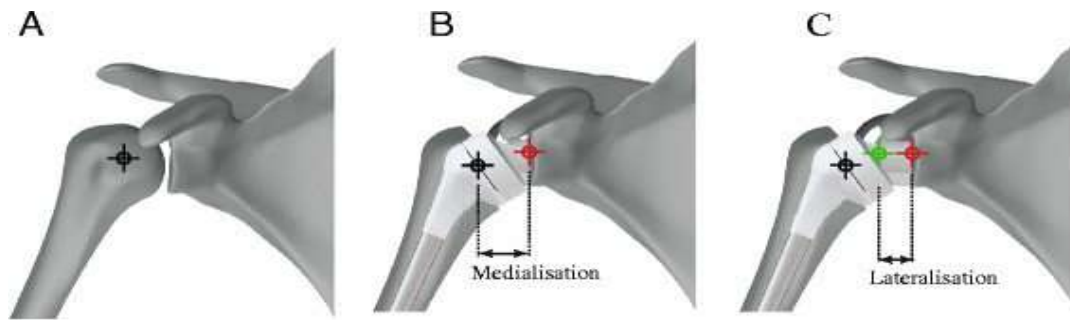
### ***Mechanical Properties of Total Shoulder Implants***

Total shoulder prostheses are biomechanically designed to mimic the range of motion, load transfer, and rotational stability of the native glenohumeral joint. Therefore, the mechanical strength, modulus of elasticity, wear resistance, and fatigue life of the implant materials and geometry are key determinants of clinical success.

### ***Humeral Component***

The humeral component is generally manufactured from titanium alloy (Ti-6Al-4V) or cobalt-chromium (Co-Cr). Titanium alloys have a hardness closer to cortical bone, with an elastic modulus of around 110 GPa, which reduces the stress shielding effect (Brizuela et al., 2019). Cobalt-chromium alloys, on the other hand, offer higher tensile strength (approximately 900–1000 MPa) and hardness, but their high elastic modulus can increase the risk of bone resorption during load transfer (Barazanchi et al., 2020).

The humeral head is most often manufactured from cobalt-chromium or ceramic materials. These materials minimize joint wear thanks to their high surface hardness and low coefficient of friction. The coefficient of friction of ceramic surfaces is approximately 0.04 (Popov, 2018).



**Figure 1. Diagram Illustrating Joint Centre of Rotation Location for the Anatomical Shoulder (a), Reverse Shoulder (b) and Reverse Shoulder with a Lateral-Offset Glenoid Component (c) (Ackland et al. 2015).**

Figure 1 shows medialization and lateralization due to a lateral offset glenoid component after reverse total shoulder arthroplasty. Black, red, and green bull's eyes indicate the joint center of rotation location for the anatomic shoulder, reverse shoulder, and reverse shoulder with a lateral offset glenoid component, respectively (Ackland et al. 2015).

We can explain the Placement and Biomechanical Effects as follows:

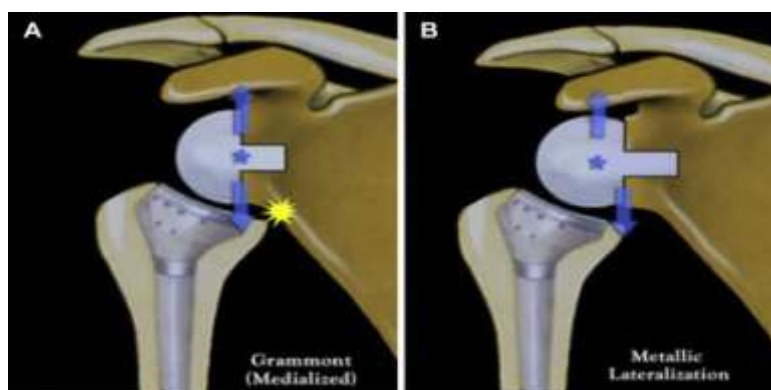
Component misplacement (e.g., excessive valgus/varus, incorrect head-shaft angle) can negatively impact joint loads. Load transfer is altered, and eccentric contact can occur on the glenoid surface (Favre et al., 2008; Büchler and Farron, 2004). The risk of malalignment increases, particularly with short shafts or shaftless systems. Cementless (press-fit) designs are becoming increasingly common. For example, one study found a significantly lower radiographic loosening rate with cementless shafts for reverse TSA. Due to the biomechanical differences between the implant and bone, bone weakening occurs in some areas. This can affect implant stability in the long term (Sanchez-Sotelo, 2021; Sanchez-Sotelo, 2011). Oversized head or overstuffed humeral components can increase soft tissue tension in the capsule/hub and impair function (Hoffman et al., 2024).

#### **Glenoid Component**

The primary material of the glenoid component is high molecular weight polyethylene (UHMWPE). UHMWPE, with its low modulus of elasticity (0.8–1.0 GPa) and high impact strength, provides optimal load distribution at the bone-implant interface (Boileau et al. 2015). However, in long-term use, polyethylene particles resulting from microwear can lead to osteolytic reactions. Therefore, the use of cross-linked polyethylene (XLPE) and antioxidant-added polyethylene has become increasingly common.

A biomechanical study has shown that component placement errors (e.g., poor positioning, high inclination) produce increased contact force and shear forces on the glenoid surface, posing a risk for loosening (Knighton et al., 2022; Goetti et al. 2021). “Rocking-horse” effect; eccentric loading of the humeral head/implant on the glenoid, lifting one side of the component and toggling the other, is associated with micromobility and loosening over time (Twomey-Kozak et al., 2024).

From a material/design perspective: For example, there is systematic evidence that all-polyethylene glenoid components may have higher long-term loosening/failure rates than metal-backed or trabecular metal-backed components (Twomey-Kozak et al., 2024).



**Figure 2. Diagrams Show Medialization of the Glenoid Component Versus Lateralization in RSA. (A) Medialization of the Center of Rotation Recruits More Deltoid Force; Thus, Increasing Muscle Utilization but Increasing the Risk of Scapular Notching and Reducing ROM. (B) (Gruber et al., 2022)**

In Figure 2, lateralization of the COR reduces the force required for the deltoid but reduces the risk of scapular notching and increases overall ROM. (Reproduced with permission from Boileau P, Moineau G, Roussanne Y, O'Shea K. Ossically augmented offset reverse shoulder arthroplasty: minimizing scapular impingement while maximizing glenoid fixation (Gruber et al., 2022).

**Mechanical Stability and Load Transfer**

Shoulder implants are subjected to complex multiaxial loading. These loads occur in the form of compression, shear, bending, and rotational moments. Therefore, not only the tensile strength of implant materials but also their fatigue life and torsional rigidity are of paramount importance.

In fatigue tests, titanium alloy implants have been reported to maintain their structural integrity under approximately  $10^7$  loading cycles (Popov, 2018). Mechanical stability also depends on the fixation method. In uncemented implants, porous surface coatings (e.g., hydroxyapatite, Ti-plasma spray) promote bone ingrowth and reduce microrelative motion. In cemented systems, the PMMA interlayer supports load transfer but carries a risk of loosening in the long term.

In TSA, mechanical stability and load transfer are closely interconnected; implant design, placement, bone quality, and soft tissue condition together determine success or failure. Glenoid bone loss and cuff condition must be evaluated (Al-Omairi et al., 2024; Mehta and Nicholson, 2023). Adequate radial mismatch between the humeral and glenoid components (e.g.,  $\geq 4-5$  mm) is preferable [78] (Hasler et al., 2020). When placing the glenoid component, proper positioning (version, inclination), fixation (peg/keel/screw), and bone alignment must be ensured (Monir et al., 2021). The humeral component must not overstuff and must be of the correct length and position. Soft tissue balance (especially the rotator cuff) must be ensured, as cuff insufficiency can impair load transfer and lead to premature component failure (Levy et al., 2016)

**Wear and Fatigue Behavior**

Wear on shoulder implants can occur through adhesive, abrasive, and fatigue-induced surface deterioration. The most common wear mechanism results from microscopic sliding movements between the humeral head and the polyethylene glenoid. This can lead to wear particles initiating an inflammatory reaction in the bone tissue (Boileau et al., 2015).

Therefore, surface engineering techniques (e.g., TiN, ZrO<sub>2</sub>, or Al<sub>2</sub>O<sub>3</sub> coatings) are used to increase wear resistance. Furthermore, high-energy gamma sterilization and cross-linking treatments are used to strengthen the molecular structure stability of polyethylene inserts.

**Table 1. Wear Resistance Comparison (Relative Scale) (Baena et al., 2015; Bhoi et al., 2022; Tapscott and Wottowa 2025)**

Material	Abrasion Resistance (relative unit)
UHMPWE	1
PEEK	2
Titanium	5
Cobalt-Crom	10

Wear resistance comparisons are examined using a relative scale in Table 1 (Baena et al., 2015; Bhoi et al., 2022 ; Tapscott and Wottowa 2025) . Cobalt-Chromium alloys provide long-term stability with high wear resistance; therefore, they are preferred for the humeral head.

**Biomechanical Adaptation and Design Parameters**

The intra-implant stress distribution is modeled using Finite Element Analysis (FEA) ( Kacsó and Peter, 2025). Load simulations determine the moments experienced during daily activities (e.g., arm elevation, rotation) (Campanelli, 2021).

Reverse shoulder prostheses provide a mechanical advantage by lengthening the deltoid muscle's power arm, but they increase the load on the glenoid component (Atrey et al., 2017).

## RESULTS

The mechanical properties of total shoulder implants play a decisive role in the long-term success and functional performance of the prosthesis. Current literature indicates that titanium and cobalt-chromium alloys, as well as UHMWPE, are sufficient in terms of biomechanical compatibility, wear resistance, and fatigue strength. When the modulus of elasticity of the humeral component is close to the cortical bone, stress protection is reduced and the risk of bone resorption is reduced. In glenoid components, microwear on polyethylene surfaces increases the risk of long-term osteolysis; therefore, cross-linked polyethylene and surface coating technologies are used.

Mechanical stability is directly related not only to material selection but also to implant geometry, axial alignment, and fixation method. Failure to achieve optimal load transfer and rotational stability increases the risk of implant loosening, increased wear, and premature failure.

Recommendations;

**Material and Surface Improvements:** Cross-linked polyethylene and ceramic coatings are recommended for glenoid components to reduce wear rates. Titanium alloys should be preferred for humeral components to reduce stress shielding.

**Optimizing Biomechanical Design:** The radius of curvature of the humeral head and the glenoid surface angle should be selected to align with the natural axes of motion of the shoulder. A personalized implant design can improve long-term rotational stability.

**Long-Term Follow-Up and Research:** Long-term prospective studies are needed to correlate polyethylene particle-induced osteolysis and implant fatigue behavior with clinical outcomes.

**Surgical Technique and Fixation:** Optimizing porous coatings and biological fixation in cementless implants and planning the use of PMMA in cementless systems will increase mechanical stability.

In conclusion, improving the mechanical performance of total shoulder implants will be possible through the integration of materials science, biomechanical design, and surgical techniques. Future research, particularly focusing on custom implants and advanced surface engineering, will significantly improve long-term prosthetic success.

## REFERENCES

1. AAOS. (2020). Management of glenohumeral joint osteoarthritis. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2020. Available from: <https://www.aaos.org/globalassets/quality-and-practice-resources/glenohumeral/gjo-cpg.pdf>. Accessed October 30, 2025.
2. Acharya, S., Soni, R., Suwas, S. and Chatterjee, K. (2021). Additive manufacturing of Co-Cr alloys for biomedical applications: a concise review. *J Mater Res*, 36, 3746-3760.
3. Ackland, D., Patel, M. and Knox, D. (2015). Prosthesis design and placement in reverse total shoulder arthroplasty. *Journal of orthopaedic surgery and research*, 10, 101.
4. Affatato, S., Ruggiero, A., Jaber, S.A., Merola, M. and Bracco, P. (2018). Wear behaviours and oxidation effects on different UHMWPE acetabular cups using a hip joint simulator. *Materials*, 11, 433.
5. Al-Omairi, S., Albadran, A., Dagher, D., Leroux, T. and Khan, M. (2024). Glenoid bone loss in shoulder arthroplasty: a narrative review. *Ann Jt*, 9, 8.
6. Atrey, A., Ward, S.E., Khoshbin, A., Hussain, N., Bogoch, E., Schemitsch, E.H. and Waddell, J.P. (2017). Ten-year follow-up study of three alternative bearing surfaces used in total hip arthroplasty in young patients: a prospective randomised controlled trial. *Bone Joint J*, 99-B(12):1590-1595.
7. Baena, J.C., Wu, J. and Peng, Z. (2015). Wear performance of UHMWPE and reinforced UHMWPE composites in arthroplasty applications: a review. *Lubricants*, 3, 413-436.
8. Baker, D.A., Hastings, R.S. and Pruitt, L. (1999). Study of fatigue resistance of chemical and radiation crosslinked medical grade ultrahigh molecular weight polyethylene. *J Biomed Mater Res*, 46(4), 573-581.
9. Barazanchi, A., Li, K.C., Al-Amleh, B., Lyons, K. and Waddell, J.N. (2020). Mechanical properties of laser-sintered 3D-printed cobalt chromium and soft-milled cobalt chromium. *Prosthesis*, 2, 313-320.
10. Baron, S., Ahearne, E., Connolly, P., Keaveney, S. and Byrne, G. (2015). An assessment of medical grade cobalt chromium alloy ASTM F1537 as a "difficult-to-cut (DTC)" material. In: Proceedings of the Machine Tool Technologies Research Foundation 2015 Annual Meeting; San Francisco.
11. Bhoi, S., Prasad, A., Kumar, A., Sarkar, R.B., Mahto, B., Meena, C.S. and Pandey, C. (2022). Experimental study to evaluate the wear performance of UHMWPE and XLPE material for orthopedics application. *Bioengineering (Basel)*, 9(11), 676.
12. Bistolfi, A., Giustra, F., Bosco, F., Sabatini, L., Aprato, A. and Bracco, P. (2021). Ultra-high molecular weight polyethylene (UHMWPE) for hip and knee arthroplasty: the present and the future. *J Orthop*, 25, 98-106.

13. Bittredge, O., Hassanin, H., El-Sayed, M.A., Eldessouky, H.M., Alsaleh, N.A., Alrasheedi, N.H., Essa, K. and Ahmadein, M. (2022). Fabrication and optimisation of Ti-6Al-4V lattice-structured total shoulder implants using laser additive manufacturing. *Materials*, 15, 3095.
14. Boileau, P., Sinnerton, R. J., Chuinard, C. and Walch, G. (2006). Arthroplasty of the shoulder. *J Bone Joint Surg Br*, 88, 562-575.
15. Boileau, P., Walch, G. and Hatzidakis, A.M. (2015). Mechanical considerations in shoulder arthroplasty. *Clinics in Orthopedic Surgery*, 7(3), 250-258.
16. Bracco, P., Bellare, A., Bistolfi, A. and Affatato, S. (2017). Ultra-high molecular weight polyethylene: influence of the chemical, physical and mechanical properties on the wear behavior. A review. *Materials (Basel)*, 10(7), 791.
17. Brizuela, A., Herrero-Climent, M., Rios-Carrasco, E., Rios-Santos, J.V., Pérez, R.A., Manero, J.M. and Gil Mur, J. (2019). Influence of the elastic modulus on the osseointegration of dental implants. *Materials (Basel)*, 12(6), 980.
18. Büchler, P. and Farron, A. (2004). Benefits of an anatomical reconstruction of the humeral head during shoulder arthroplasty: a finite element analysis. *Clin Biomech (Bristol)*, 19(1), 16-23.
19. Campanelli, L. (2021). A review on the recent advances concerning the fatigue performance of titanium alloys for orthopedic applications. *Journal of Materials Research*, 36, 151-165.
20. Castagna, A., Randelli, M., Garofalo, R., Maradei, L., Giardella, A., Borroni, M. (2010). Mid-term results of a metal-backed glenoid component in total shoulder replacement. *J Bone Joint Surg Br*, 92, 1410-1415.
21. Chen, Q. and Thouas, G.A. (2015). Metallic implant biomaterials. *Mater Sci Eng R Rep*, 87, 1-57.
22. Chen, R.E., Knapp, E., Qiu, B., Miniaci, A., Awad, H.A. and Voloshin, I. (2022). Biomechanical comparison of stemless humeral components in total shoulder arthroplasty. *Seminars in Arthroplasty*, 32, 145-153.
23. De Wilde, L., Dayerizadeh, N., De Neve, F., Basamania, C. and Van Tongel, A. (2013). Fully uncemented glenoid component in total shoulder arthroplasty. *J Shoulder Elb Surg*, 22, E1-E7.
24. Edmonds, A. (2016). Shoulder arthroplasty. In: Saunders, R., Astifids, R., Burke, S., Higgins, J. and McClinton, M., editors. *Hand and Upper Extremity Rehabilitation: A Practical Guide*. 4th ed. Elsevier Inc. p. 283-290.
25. Erickson, B. J., Chalmers, P. N., Denard, P. J., Gobezie, R., Romeo, A. A. and Lederman, E. S. (2020). Current state of short-stem implants in total shoulder arthroplasty: A systematic review of the literature. *JSES Int*; 4, 114-119.
26. Favre, P., Moor, B., Snedeker, J.G. and Gerber, C. (2008). Influence of component positioning on impingement in conventional total shoulder arthroplasty. *Clin Biomech (Bristol)*, 23(2), 175-183.
27. Flatow, E. L. and Harrison, A. K. (2011). A history of reverse total shoulder arthroplasty. *Clin Orthop Relat Res*, 469, 2432-2439.
28. Fucetese, S., Costouros, J., Kühnel, S. and Gerber, C. (2010). Total shoulder arthroplasty with an uncemented soft-metal-backed glenoid component. *J Shoulder Elbow Surg*, 19, 624-631.
29. Gessner, B.D., Steck, T., Woelber, E. and Tower, S.S. (2019). A systematic review of systemic cobaltism after wear or corrosion of chrome-cobalt hip implants. *J Patient Saf*, 15(2), 97-104.
30. Godeneche, A., Boileau, P., Favard, L., Le Huec, J. C., Levigne, C., Nove-Josserand, L. et al. (2002). Prosthetic replacement in the treatment of osteoarthritis of the shoulder: Early results of 268 cases. *J Shoulder Elbow Surg*, 11, 11-18.
31. Goetti, P., Denard, P.J., Collin, P., Ibrahim, M., Mazzolari, A. and Lädermann, A. (2021). Biomechanics of anatomic and reverse shoulder arthroplasty. *EFORT Open Rev*; 6(10), 918-931.
32. Goldberg, J.R. and Gilbert, J.L. (2004). The electrochemical and mechanical behavior of passivated and TiN/AlN-coated CoCrMo and Ti6Al4V alloys. *Biomaterials*, 25(5), 851-864.
33. Gruber, M., Kirloskar, K., Werner, B., Lädermann, A. and Denard, P. (2022). Factors associated with internal rotation following reverse shoulder arthroplasty: a narrative review. *JSES Reviews, Reports, and Techniques*, 2, 117-124.
34. Harmer, L., Throckmorton, T. and Sperling, J. W. (2016). Total shoulder arthroplasty: Are the humeral components getting shorter? *Curr Rev Musculoskelet Med*, 9, 17-22.
35. Hasler, A., Meyer, D.C., Tondelli, T. et al. (2020). Radiographic performance depends on the radial glenohumeral mismatch in total shoulder arthroplasty. *BMC Musculoskelet Disord*, 21, 206.
36. Hoffman, R.A., Covarrubias, O., Agaisse, T., Portnoff, B. and Green, A. (2024). How anatomic should anatomic total shoulder arthroplasty be? Evaluation of humeral head reconstruction with the best-fit circle. *J Shoulder Elbow Surg*, 33(6), S43-S48.
37. Iqbal, S., Jacobs, U., Akhtar, A., Macfarlane, R. J. and Waseem, M. (2013). A history of shoulder surgery. *Open Orthop J*, 7, 305-309.
38. Kacsó, A.B. and Peter, I. (2025). A review of past research and some future perspectives regarding titanium alloys in biomedical applications. *J Funct Biomater*, 16(4), 144.
39. Killian, C., Press, C., Smith, K. et al. (2017). Radiographic and clinical comparison of pegged and keeled glenoid components using modern cementing techniques: Midterm results of a prospective randomized study. *J Bone Joint Surg*, 26, 2078-2085.
40. Knighton, T.W., Chalmers, P.N., Sulkar, H.J., Aliaj, K., Tashjian, R.Z. and Henninger, H.B. (2022). Anatomic total shoulder glenoid component inclination affects glenohumeral kinetics during abduction: a cadaveric study. *J Shoulder Elbow Surg*, 31(10), 2023-2033.
41. Kodama, T. (1989). Study on biocompatibility of titanium alloys. *Kokubyo Gakkai Zasshi*; 56, 263-288.

42. Kurtz, S. (2004). The UHMWPE handbook: ultra-high molecular weight polyethylene in total joint replacement. Elsevier.
43. Kurtz, S.M., Muratoglu, O.K., Evans, M. and Edidin, A.A. (1999). Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. *Biomaterials*, 20(18), 1659-1688.
44. Lazarus, M., Jensen, K., Southworth, C. and Matsen, F. I. (2002). The radiographic evaluation of keeled and pegged glenoid component insertion. *J Bone Joint Surg Am*, 84-A, 1174-1182.
45. Leafblad, N., Asghar, E. and Tashjian, R.Z. (2022). Innovations in shoulder arthroplasty. *J Clin Med*, 11(10), 2799.
46. Lemons, J.E., Niemann, K.M.W. and Weiss, A.B. (1976). Biocompatibility studies on surgical-grade titanium-, cobalt-, and iron-base alloys. *J Biomed Mater Res*, 10, 549-553.
47. Levy, D.M., Abrams, G.D., Harris, J.D., Bach, B.R. Jr, Nicholson, G.P. and Romeo, A.A. (2016). Rotator cuff tears after total shoulder arthroplasty in primary osteoarthritis: a systematic review. *Int J Shoulder Surg*, 10(2), 78-84.
48. Lin, D. J., Wong, T. T. and Kazam, J. K. (2016). Shoulder arthroplasty, from indications to complications: What the radiologist needs to know. *Radiographics*, 36, 192-208.
49. Marti, A. (2000). Cobalt-base alloys used in bone surgery. *Injury*, 31, D18-D21.
50. Mehta, N. and Nicholson, G.P. (2023). Management of glenoid bone loss in primary reverse total shoulder arthroplasty. *Curr Rev Musculoskelet Med*, 16(8), 358-370.
51. Mehta, N., Hall, D., Pourzal, R. and Garrigues, G. (2020). The biomaterials of total shoulder arthroplasty: their features, function, and effect on outcomes. *JBJS Rev*, 8, e1900212.
52. Michel, P.A., Katthagen, J.C., Schliemann, B., Wilkens, S., Frank, A., Heilmann, L.F., Dyrna, F. and Raschke, M.J. (2021). Biomechanical value of a protective proximal humeral cerclage in reverse total shoulder arthroplasty. *Journal of Clinical Medicine*, 10, 4600.
53. Monir, J.G., Hao, K.A., Abeyewardene, D., O'Keefe, K.J., King, J.J., Wright, T.W. and Schoch, B.S. (2021). Extra-short humeral heads reduce glenohumeral joint overstuffing compared with short heads in anatomic total shoulder arthroplasty. *JSES Int*, 6(2), 209-215.
54. Neer, C. S. (1974). Replacement arthroplasty for glenohumeral osteoarthritis. *J Bone Joint Surg Am*, 56, 1-13.
55. Neer, C.S. (1955). Articular replacement for the humeral head. *J Bone Joint Surg Am*, 37(2), 215-228.
56. Pais, I., Fehér, M., Farkas, E., Szabó, Z. and Cornides, I. (1977). Titanium as a new trace element. *Commun Soil Sci Plant Anal*; 8, 407-410.
57. Papadonikolakis, A. and Matsen, F. A. I. (2014). Metal-backed glenoid components have a higher rate of failure and fail by different modes in comparison with all-polyethylene components. *J Bone Joint Surg*, 96, 1041-1047.
58. Park, C.N., Zhang, G.X., Chang, J. et al. (2023). Pyrocarbon hemiarthroplasty of the shoulder: a systematic review and meta-analyses of clinical results. *J Shoulder Elbow Surg*, 2023, 1.
59. Popov, V.L. (2018). Contact mechanics and friction in orthopaedic implants. Springer.
60. Quinn, J., McFadden, R., Chan, C-W. and Carson, L. (2020). Titanium for orthopedic applications: an overview of surface modification to improve biocompatibility and prevent bacterial biofilm formation. *iScience*, 23, 101745.
61. Ramírez-Vidaurre, L.E., Castro-Román, M., Herrera-Trejo, M., García-López, C.V. and Almanza Casas, E. (2009). Cooling rate and carbon content effect on the fraction of secondary phases precipitate in as-cast microstructure of ASTM F75 alloy. *Journal of Materials Processing Technology*, 209(4), 1681-1687.
62. Randelli, P., Cucchi, D. and Butt, U. (2016). History of shoulder instability surgery. *Knee Surg Sports Traumatol Arthrosc*, 24(2), 305-329.
63. Razfar, N., Reeves, J. M., Langohr, D. G., Willing, R., Athwal, G. S. and Johnson, J. A. (2016). Comparison of proximal humeral bone stresses between stemless, short stem, and standard stem length: A finite element analysis. *J Shoulder Elb Surg*, 25, 1076-1083.
64. Ryan, W.K., Van De Voort, W., Saad, M.A., Wu, E., Garcia-Nolen, T.C., Bayne, C.O. and Szabo, R.M. (2023). The effect of shoulder prosthesis stem length on failure due to torsional loading: a biomechanical study in composite humeri. *JSES International*, 7, 819-826.
65. Saini, M., Singh, Y., Arora, P., Arora, V. and Jain, K. (2015). Implant biomaterials: a comprehensive review. *World J Clin Cases*, 3(1), 52-57.
66. Sanchez-Sotelo, J. (2011). Total shoulder arthroplasty. *The Open Orthopaedics Journal*, 5, 106-114.
67. Sanchez-Sotelo, J. (2021). Current concepts in humeral component design for anatomic and reverse shoulder arthroplasty. *J Clin Med*, 10(21), 5151.
68. Sarraf, M., Rezvani Ghomi, E., Alipour, S., Ramakrishna, S. and Liana Sukiman, N. (2022). A state-of-the-art review of the fabrication and characteristics of titanium and its alloys for biomedical applications. *Bio-Des Manuf*, 5, 371-395.
69. Sharplin, P. K., Frampton, C. M. A., Hirner, M. (2020). Cemented vs. uncemented glenoid fixation in total shoulder arthroplasty for osteoarthritis: A New Zealand Joint Registry study. *J Shoulder Elbow Surg*, 29, 2097-2103.
70. Singh, J. A., Sperling, J. W., Cofield, R. H. (2011). Revision surgery following total shoulder arthroplasty: Analysis of 2588 shoulders over three decades (1976 to 2008). *The Journal of Bone & Joint Surgery British Volume*; 93-B, 1513-1517.

71. Sperling, J. W., Cofield, R. H., O'Driscoll, S. W., Torchia, M. E. and Rowland, C. M. (2000). Radiographic assessment of ingrowth total shoulder arthroplasty. *J Shoulder Elbow Surg*, 9, 507-513.
72. Taddei, P., Pavoni, E. and Affatato, S. (2017). Comparative micro-Raman study on standard, cross-linked and vitamin E-blended polyethylene acetabular cups after long-term in vitro testing and ageing. *J Raman Spectrosc*, 48, 1065-1074.
73. Tapscott DC, Wottowa C. (2025). Orthopedic Implant Materials. [Updated 2023 Jul 25]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing.
74. Throckmorton, T., Zarkadas, P., Sperling, J., Cofield, R. (2019). Pegged versus keeled glenoid components in total shoulder arthroplasty. *J Shoulder Elbow Surg*, 19, 726-733.
75. Tsai, C-H., Hung, C-H., Kuo, C-N., Chen, C-Y., Peng, Y-N. and Shie, M.Y. (2019). Improved bioactivity of 3D printed porous titanium alloy scaffold with chitosan/magnesium-calcium silicate composite for orthopaedic applications. *Materials*, 12(2):, 203.
76. Twomey-Kozak, J., Adu-Kwarteng, K., Lunn, K., Briggs, D.V., Hurley, E., Anakwenze, O.A. and Klifto, C.S. (2024). Recent advances in the design and application of shoulder arthroplasty implant systems and their impact on clinical outcomes: a comprehensive review. *Orthop Res Rev*, 16, 205-220.
77. Vaicelyte, A., Janssen, C., Le Borgne, M. and Grosogeat, B. (2020). Cobalt-chromium dental alloys: metal exposures, toxicological risks, CMR classification, and EU regulatory framework. *Crystals*; 10(12), 1151.
78. Verestiue, L., Spataru, M.-C., Baltatu, M. S., Butnaru, M., Solcan, C., Sandu, A. V., Voiculescu, I., Geanta, V. and Vizureanu, P. (2021). New Ti-Mo-Si materials for bone prosthesis applications. *J Mech Behav Biomed Mater*, 113, 104198.
79. Waizy, H., Seitz, J. M., Reinfenrath, J., Weizbauer, A., Bach, F. W., Meyer-Lindenberg, A., Denkena, B. and Windhagen, H. (2013). Biodegradable magnesium implants for orthopedic applications. *J Mater Sci*, 48(1), 39-50.
80. Wallace, A. L., Phillips, R. I., MacDougal, G. A., Walsh, W. R., Sonnabend, D. H. (1999). Resurfacing of the glenoid in total shoulder arthroplasty: A comparison, at a mean of five years, of prostheses inserted with and without cement. *J Bone Joint Surg Am*, 81, 510-518.
81. Wang, V.M., Krishnan, R., Ugwonal, O.F.C., Flatow, E.L., Bigliani, L.U. and Ateshian, G.A. (2005). Biomechanical evaluation of a novel glenoid design in total shoulder arthroplasty. *J Shoulder Elbow Surg*, 14(1), 129-140.
82. Wirth, M. A., Lored, R., Garcia, G., Rockwood, C. A. Jr., Southworth, C., Iannotti, J. P. (2012). Total shoulder arthroplasty with an all-polyethylene pegged bone-ingrowth glenoid component: A clinical and radiographic outcome study. *J Bone Joint Surg Am*, 1, 260-267.
83. Wodarek, J. and Shields, E. (2021). Stemless total shoulder: A review of biomechanical fixation and recent results. *J Shoulder Elb Arthroplast*, 5, 247154922110084.
84. Zilber, S. (2017). Shoulder arthroplasty: historical considerations. *Open Orthop J*, 11, 1100-1107.