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Original Research Paper

To study the examination of stress and tributological properties in relation to an artificial human knee joint

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ABSTRACT:

The examination of stress and tribological properties in artificial human knee joints is a crucial aspect of biomedical engineering and orthopaedics. This study highlights the importance of understanding the mechanical stresses and tribological interactions within these artificial knee joints, with a focus on improving their longevity and patient satisfaction. Stress analysis is essential to ensure that artificial knee joints can with stand the complex mechanical forces encountered during daily activities, reducing the risk of component failures and bone damage, ultimately leading to fewer revision surgeries. The main objective of the study is to examination of stress and tribological properties in relation to an artificial human knee joint. In this study we use secondary research approach. Therefore, data has been collected from several journals, researches, articles, books, library data, organizational reports, websites, etc. to fulfil the objective of this study. Moreover, tribological properties, such as friction, wear, and lubrication, play a pivotal role in the performance and durability of artificial knee joints. Achieving low friction, minimal wear, and proper lubrication is crucial for preventing complications and ensuring patient comfort. The choice of materials, including metal-polymer combinations, is critical for the success of knee replacement surgeries. Advancements in technology, such as robotic-assisted procedures, have improved precision, recovery times, and reduced complications. However, the longevity of artificial knee joints depends on patient-specific factors and surgical quality. In this, research field has significantly advanced the understanding and treatment of knee joint diseases and injuries, but ongoing innovation and multidisciplinary collaboration are needed to further enhance patient quality of life.

Keywords: Artificial knee joint, Stress, Tribological properties

INTROCUCTION:

The stress and tribological properties of an artificial human knee joint are important factors that affect the performance and durability of the implant. The stress refers to the internal forces that act on the materials of the implant and the surrounding bone and cartilage, while the tribology refers to the friction, wear, and lubrication of the articulating surfaces of the implant. These properties depend on various factors, such as the design, material, and alignment of the implant, as well as the loading and kinematics of the knee joint.

Stress within the context of artificial knee joints refers to the internal forces and mechanical loads experienced by the components and materials of the prosthesis during movement and weight-bearing activities. These stresses are influenced by various factors, including the design of the prosthesis, the patient's activity level, and the materials used in its construction. Proper stress analysis is crucial to ensure the artificial knee joint can withstand the demands of daily life and provide a comfortable, natural range of motion.

On the other hand, tribological properties are a fundamental aspect of the functioning of artificial knee joints. Tribology is the study of friction, wear, and lubrication in moving mechanical systems. In the context of knee prostheses, tribological properties encompass the interactions between the articulating surfaces, including the femoral and tibial components, and any associated bearing materials or lubricants. Achieving low friction, minimal wear, and adequate lubrication is essential to prevent complications such as implant failure, tissue inflammation, and discomfort for the patient.

These studies provide valuable insights into the stress and tribological properties of artificial knee joints, which can help to improve the design and development of more durable and biocompatible implants. However, there are still some challenges and limitations in this field, such as the lack of standardized testing methods, the complexity of modelling realistic loading and boundary conditions, the variability of patient-specific factors, and the interaction between biomechanics and wear. Therefore, further research is needed to address these issues and to optimize the stress and tribological performance of artificial knee joints.(Mohammad Mostakhdemin, 2021).

TRIBOLOGY OF ARTIFICIAL KNEE JOINT:

The artificial knee consists of three parts: the tibial, femoral, and patellar components. The patella, located at the front of the knee, is attached to the femur, located at the top of the thigh, and the tibia, located at the top of the shin. The femoral and tibial components form a sliding contact that mimics the natural motion of the knee joint. The patellar component glides over the front of the femoral component during bending and straightening of the knee.

The materials common used for the artificial knee joint are metal alloys, such as cobalt-chromium-molybdenum (CoCrMo), titanium-aluminum-vanadium (TiAlV), or stainless steel; ceramics, such as alumina (Al2O3), zirconia (ZrO2), or silicon nitride (Si3N4); and polymers, such as ultra-high molecular weight polyethylene (UHMWPE), polyetheretherketone (PEEK), or polyvinyl alcohol (PVA). The metal alloys are usually used for the femoral and patellar components, while the ceramics or polymers are used for the tibial component. The combination of metal and polymer is the most widely used material pair for artificial knee joints, due to its low friction and high wear resistance.

The tribology of artificial knee joint is influenced by many factors, such as the material properties, surface roughness, loading, lubrication, inflammation, infection etc. The tribology of artificial knee joint is also affected by the patient-specific factors, such as age, weight, activity level, bone quality, muscle strength, and joint stability. The tribology of artificial knee joint can be evaluated by various methods, such as laboratory tests, computational simulations, clinical studies, and retrieval analyses. The ultimate goal of tribology of artificial knee joint is to improve the quality of life of patients who suffer from knee joint diseases by providing them with reliable, durable, and comfortable artificial knee joints.(Z. et al., 2019)

Joint Replacements:

Every year, more than two million artificial joints are replaced throughout the world. Ten percent of implants (most often hip replacements) need revision surgery during the first decade. The typical life expectancy of a knee joint is just 5-6 years, yet knee replacement surgery is on the increase in India. Younger and heavier folks have a worse prognosis.(Hench, 2005).

At the age of 30, the revision rate for surgery is about 33 percent. This is why research on the longevity of artificial joints is ongoing. A plastic-coated stem for an isoelastic hip prosthesis has also been introduced lately. You may recall that contact stress at the articulating surface plays a crucial role in the aging process.(Foran, 2021)

High Tech Knee Replacement:

Surgeons can replace a patient's knee with precision and ease utilizing cutting-edge techniques and tools. The success rate of total knee replacement procedures has increased as a result of medical advances in recent years. The robotic arm, which can install implants with extreme precision, has changed the face of knee replacement surgery. Individualized surgical procedures are now possible with the use of 3D CT planning software and a robotic arm. Cementless implants for complete knee replacements are also becoming more popular. Cementless total knee arthroplasty is preferable for obese patients (Hammel, 2022).

Cementless implants may survive far longer than traditional prosthetic joints. Using GPS during knee surgery might help both the surgeon and the patient. In order to better map the patient's anatomy, companies like OrthAlign have developed computer-assisted technologies to use during knee surgery. New computer-assisted and robotic surgical instruments have given doctors a leg up in their efforts to keep their elderly patients mobile and independent for as long as possible (Mymosh, 2008)

Knee Joint:

The modern era of total knee replacement was ushered in by Gunston's introduction of the first minimally invasive full knee components in 1971. (Walldmel al 1950) designed hinged implants to replace both joint surfaces, which increased stability and limb alignment. Biomechanical research and clinical assessments of the knee led to the development of the second generation of TKR, which provides a wider range of motion in all directions (including flexion, extension, adduction, abduction, and rotation). The typical knee joint is seen in sagittal and frontal perspectives.(Jha, 2022)

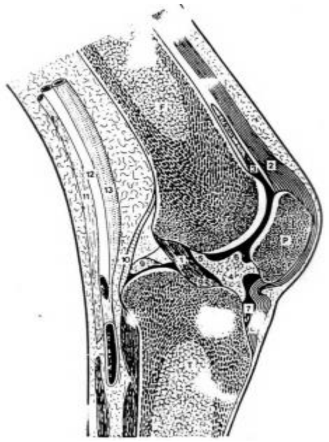

Fig. 1 natural right knee joint at sagittal plane

Component loosening:

During sterile treatment, prostheses that include a tibia) component that is totally or partly constrained at the tibia) often fail. The metal femoral component seldom becomes dislodged. The majority of surgically restored joints remain stable for at least 5 years after the treatment, with just 3-5% eventually loosening sterilely. This is because to developments in the method of making implants and the apparatus they sit inside. Restoration of normal limb alignment, the use of low viscosity cement, and advancements in quality instrumentation have all contributed to a significant decrease in loosening. The multiplication of big cells and the rattling of parts have both been connected to particulate illness, which in turn is caused by wear debris.(Watters, 2010)

Component breakage:

It is quite unusual for a knee prosthesis, particularly a hinged one, to break. However, localized, semi-confined fatigue failure had occurred in the metal. There have been a few reported examples of polyethylene breakdown, most of which occurred during the prototyping stage of ultra-thin polyethylene components. Lighter, higher-strength alloy and better design are reducing the frequency of knee arthroplasty component failure.(Patel, 2016)

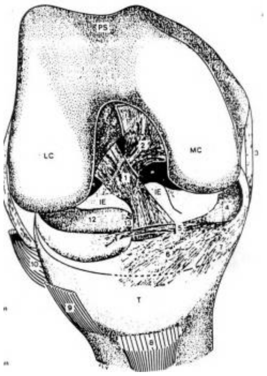

Fig.2 natural knee joint at frontal plane

Wear and Deformation:

Research shows that knee prosthesis have a much shorter lifespan than hip prostheses. Modern prosthetic limbs are constructed from UHMWPE (ultrahigh molecular weight polyethylene). It has proven effective as a material for orthopaedic implants. Massachusetts General Hospital and Harvard Medical School researchers evaluated failed total hip and knee replacements caused by PE wear debris in 1994. Excessive PE debris, like PMMA debris, was strongly associated with the occurrence of loosening.(Ludema, 2010)

Total knee replacements (1994 and 20 others) have come under fire for failing too soon owing to the tibial component's polyethylene (PE) wearing out too quickly. Schmalzried et al.'s prediction that THR would generate more submicron PE particles and comparatively fewer big particles as wear debris holds true; in contrast, TKR prosthesis generate a more homogeneous particle population with fewer submicron particles. Bone loss around the prosthesis was also demonstrated to vary between total knee replacements and total hip replacements.(Adams, 2015)

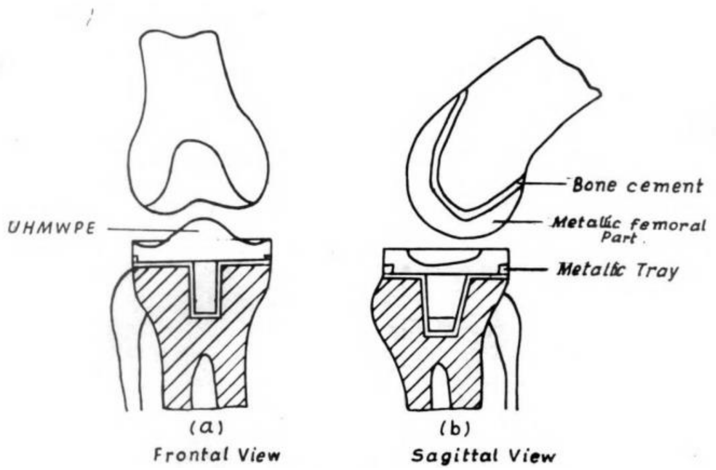

Fig.3 artificial knee joint

Friction and lubrication in artificial joints:

These days, a metal ball is placed inside of a polyethylene (UHMWPE) cup to create a prosthetic hip. Charnley joints employ a femoral replacement with a radius of 11 mm made of stainless steel, whereas Muller joints use a femoral replacement made of a cobalt chromium molybdenum alloy with a radius of 16 mm. UHMWPE is used in the majority of hip replacement sockets, whereas ceramic femoral heads are used in a minority of procedures.(Scholes & Unsworth, 2006)

Hip joint:

Although metal-on-metal connections are becoming rarer, they are still in use by certain older generations. Cobalt, chromium, and molybdenum alloys were often used in their production. The recent uptick in the use of metal-on-metal prostheses in continental Europe is an interesting development. McKee-Farrar all-metal hip joint friction coefficient vs. quR/P for various synthetic lubricants. If the synovial fluid were typical in viscosity, the indicated vertical line on the graph would represent the highest value of quR/P that could be anticipated. Since the fluid in these prosthetic joints is meant to mimic the state of an arthritic joint, it is engineered to be less viscous than typical. The fluid layer lubrication shown on the cobalt chrome molybdenum artificial joint cannot be provided by synovial fluid. When two metals touch, the coefficient of friction increases to roughly 0.3. Even with high-viscosity fluid film lubrication, the friction at these joints is significant. Metal-on-metal joints are strong and long-lasting, but they lack the fluid layer lubrication of organic joints. Charnley joints get more from synovial fluid's friction-reducing properties than McKee-Farrar joints do, but synovial fluid still can't provide full fluid film lubrication. The friction coefficient, however, is drastically lowered. (Ghalme et al., 2016)

Wear of artificial joints:

A number of prosthetic joints have a lifespan of just 10 years. Normal wear and tear, or a weakening of the joint inside the bone, are also potential causes of prosthesis failure. The only solution is artificial joint replacement surgery. Increased friction and wear of the acetabular component may contribute to loosening because it may cause the stress vectors acting on the cement anchoring the component to the bone to shift. Bone loss may occur as a result of contact between a prosthesis and particles from wear.

Knee Replacement Contact Stress and Strain Analysis of the Tibia and the Femur. Aseptic loosening without metal-backed tibial trays led to the breakdown of the knee system. The metal support reduces pressure on the trabecular bone, and the aseptic loosening of the polyethylene trays in positions 4 and 5 makes them more flexible. Metal-backed trays reduce loosening, therefore polyethylene wear tends to restrict knee system longevity.(Currey, 2013)

Wear tests show polyethylene preparations' wear resistance but not clinically expected wear patterns or locations. Computer-based stress analysis may reveal knee stresses and their effects on implant form and size, but model preparation time limits its use to a few implant designs. Wear simulators replicate muscular forces and component body weight loads and need complex servohydraulic testing equipment. Wear testing 10 million cycles may take over 2 months, making clinically viable implant designs in different sizes uncomparable. This may forecast clinical implant wear rates and find and shape wear areas. 13-17 Benchtop contact stress and wear are linked. Thus, contact stress should show wear. This procedure doesn't always match clinical retrieval wear. Despite the identical implant design, wear patterns vary according to materials properties and subsurface forces.(Dowson, 2002)

Contact in the Prosthetic Joints:

To be comfortable, prostheses must replace damaged articulating surfaces and limit bone-component movement. Ligaments and articular surfaces must match for knee lateral stability. Gunston employed polycentric knee arthoplasty in 1971 with two stainless steel semicircular runners bonded into femoral condyle holes. HOPE polymers in tibial plateaus troubled athletes.

Since then, condylar replacement knees have been created utilizing several criteria, making them suitable for certain demands but not others. Cam mechanisms and surface dishing may help patella lever arms (Burstein 1984). Also, daily laxity with increasing restraint from neutral (Thatcher et al., 1987. It proposed a knee prosthesis with -12*to + 12" internal/external rotation and 13 mm anterior-posterior displacement for varied occupations. (Smith, 2019)

It attempted to connect femoral and tibial condyle curvatures to loads and moments. Contact forces may produce plastic wear and deformation due to the relative geometry of the femoral and tibial surfaces, according to Bartel et al. (1986). Flat tibial surfaces exhibited the highest stresses and single-axis cylindrical surfaces the lowest, according to Walker (1988).

According to Landy and Walker (1988), tension does not inevitably wear out components. Modern designs allow posterior cruciate ligament shear stress and varied position and motion patterns owing to decreased sagittal plane conformance. Option: resect both cruciates for anterior-posterior stability, reduced contact stresses, and improved posterior surfaces. Most designs enable size exchange to fit bones closely. A big femoral component may fit a regular tibia.(Johnson, 2015)

Articular and Artificial Cartilage, Characteristics and Properties:

The Structure of Articular Cartilage:

Denser, misaligned GAGs, chondrocytes, and collagen weaken AC structure. The main components are water (60–85%), collagen type II (15–22%), and PG (4–7%). The deep zone contains vertical hydroxyapatite (Hap), collagen, and chondrocytes. Anisotropic, viscoelastic, inhomogeneous biphasic AC isn't linear.(Rodeo, 2009)

Characteristics of Articular Cartilage:

AC can withstand 100–200 million loads. AC is viscoelastic due to strain rate. Loading direction affects anisotropic tensile stiffness. AC has uneven tension and compression from surface to depth. AC integration with incompressible, pressurized synovial fluid maximizes joint contact pressure. These qualities provide cartilage a unique structure to sustain cyclic physical stress and smoothly transmit loads to bones.

Walking AC experiences 3–5 MPa hip and knee contact stresses. Both the compressive and shear moduli of cartilage are very low, at less than 1.5 and 0.5 MPa, respectively. Between 0.34 and 0.48, Poisson's ratio may be found. AC is permeable because its stiffness varies with the strain rate. In particular, the results show that the AC reaction is a consolidation-type deformation that is sensitive to material stiffness at low strain-rates (0.01 > (t)). Hyperelastic deformation with strain rates of 0.01 (t) or less produces high stiffness and is considered the standard for elastic deformation. Strain rate increased from 2.7 103 s1 to 3.5 102 s1 when cartilage stiffness was increased, as determined by Eric et al. Two AC mechanical responses were found at various strain rates. Low strain rates considerably enhance stiffness. Stiffness remains constant at greater strain rates. Beyond a threshold, high-strain rate loading little affects stiffness. AC compressive response is strain-rate dependent at low strain-rate.(Sophia Fox, A.J., 2009)

ECM greatly impacts AC mechanical characteristics. AC responds time-dependently with viscoelasticity, poroelasticity, or both. Research shows that PGs and chondrocyte organization affect AC load response. However, cartilage's viscoelasticity allows solid and fluid phase integration and fluid movement across the solid architecture to maintain inner tissue connections. AC's viscoelastic or poroelastic status depends on test conditions such indenter size, depth, and strain rates. Proved that AC is better modeled as a nonlinear biphasic material, not as a traditional poroelastic or viscoelastic material.(Bian, L., and Mauck, 2010)

Tribological Properties of Articular Cartilage:

Daily activities stress knees and hips a million times. ACL tears and OA risk result from joint kinematics misalignment. ACL and meniscus damage increases tribological contact stresses due to joint instability and tibial plateau acute fibrillation. Studies reveal that cartilage properties change with local contact stresses and mechanical environment, whereas tribology is location-independent. Regardless of cartilage location, joint mechanics impact tribology. The first of four healthy cartilage tribological reactions is location-specific damage tolerance. Material properties are greatly impacted by OA. Third, healthy and OA tibial plateau cartilage vary. Changes in OA tissue tribology cause biomechanical deterioration, shear stresses, and failure. Because cartilage is avascular, superficial to deep zones lose material via thickness. Microstress from cyclic loading destroys cartilage. Fraying occurs when AC collagen fibers are sheared. AC degeneration occurs when damage to fibers surpasses the capacity of cells to repair them. AC may be destroyed by dryness, aberrant loading from varus or valgus knee posture, aging, and excessive physiological activity, despite its rubbery surface and low wear rate and CoF.(Mow, V.C., 2018)

Asperity and friction wear. AC abrasion is challenging. PG loss and collagen network changes wear cartilage. Biochemical deterioration and biomechanical variables such knee misalignment, which increases medial or lateral knee joint pressure, may cause cartilage attrition. Complexity makes friction dominate wear research. Many investigations using metal abraders to quantify AC wear depth found that trypsin-containing synovial fluid preserves cartilage. Contact pressure, area, and sliding speed enhance wear, another research found. Biochemistry of collagen and GAGs measures wear.(Wang, C.C., and Yang, 2011)

The Interaction between the Biomechanics and Wear of Artificial Knee Joint:

Biomechanical and wear studies of prosthetic knee joints are seldom performed in isolation from one another. UHMWPE alters the in-vivo wear dynamics of the components that make up a prosthetic knee. Implant wear is caused by the breakdown of UHMWPE due to the biomechanical and tribological complexity present in vivo. UHMWPE implant wear and biomechanics remain mostly uncharted. In this research, MSK MBD and FEA were used to create a computerized method to anticipate knee wear.

Wear on a TKA may be affected by variations in joint kinematics and dynamic stresses experienced in vivo. This is the typical stopping point for wear studies. It is innovative to use a TKA FE contact mechanics and wear model for wear prediction in conjunction with a lower extremity MSK MBD model. At each node and time step, the FE model estimates the contact pressure, area, and sliding lengths of the UHMWPE insert based on the pressures applied on the knee joint and gait cycle motions. FEA may be used to study the effects of contact surface wear and creep. In the subsequent FEA, the worn insert shape from the MSK MBD model is used to produce patient-specific boundary conditions.

Motion of the TF, contact forces, and volumetric wear are all affected by articular surface wear of UHMWPE implants and knee kinematics in vivo. Results from the linked model showed that wear metrics, such as average contact area, cross-shear ratio, volumetric wear, wear area, and linear wear depth, all increased with time. The functional outcomes of TKA may be enhanced by using the patient-specific coupled wear prediction approach, which takes into account in vivo knee joint dynamics loading scenarios and the relationship between knee joint dynamics, contact mechanics, and wear.(Fregly, B. J., & Sawyer, 2012)

Important Factors on Biomechanics and Wear of Artificial Knee Joint:

Clinical data shows that TKA patients experience wear failure due to differences in prosthetic knee joint kinematics and tribology. Prostheses are not a one-size-fits-all solution due to differences in joint loads and anatomy, as well as differences in prosthetic design and surgical alignment. A TKA with a UHMWPE implant was destined to failure for a number of reasons. Surgeons and patients alike need a thorough grasp of the elements that contribute most to total knee replacement (TKR) success and how they may be adjusted to each person. Improving the longevity of UHMWPE implants relies heavily on the findings of this study. The biomechanics and durability of prosthetic knees may be influenced by a variety of factors, including implant type, material, surgical method, and patient characteristics.(Joshi, A., & Hardinge, 2009)

Effect of Patient Factors:

The biomechanics of a patient's joints may be affected by the way they walk. It was shown that knee adduction, flexion, and rotation are significantly impacted by pelvic rotation, hip abduction, and knee flexion. Walking may affect joint loads and UHMWPE wear by changing joint kinematics. A cause-and-effect" link between joint kinematics and moments evaluates TKA UHMWPE inserts.

There were considerable knee contact mechanical variations across gait styles. A medial thrust gait reduced the patient's stance phase medial contact force by 16%. Compared to the patient's regular gait, trekking pole walking decreased medial contact force by 27% in the stance phase and lateral and total contact force by 11% and 21%. A walking pole gait showed TKA patients may minimize medial, lateral, and total contact force. Strides affect knee stress and UHMWPE implant durability.

To reduce knee joint stress after TKA, clinicians propose gait adjustment with minimal gait kinematics. Modifying knee joint stress prolongs prosthetic knee joint life and minimizes UHMWPE degradation. Marzieh et al. predicted a walking style that reduced UHMWPE insert bearing surface contact pressure using neural network–genetics. Optimization may reduce knee contact pressure by 25% above standard gait rehabilitations. Best gait pattern may influence postoperative care.(Thomas, 2016)

Obesity may damage knees. Many TKA patients are fat. Obese individuals had worse postoperative Knee Society assessments. observed. Obesity may enhance UHMWPE implant wear owing to articular loading. Joint forces and motion depend on patient BMI, whereas knee joint contact mechanics and kinematics directly influence tibial insert bearing surface degradation. More unit BW raises knee contact forces 2.5-fold with the same gait. BMI increased muscle and tibiofemoral compressive and shear stresses. Poor knee prosthesis implantation and soft tissue balance affect knee biomechanics with obesity.

Lower artificial knee joint survival:

Additionally, prosthetic knee joint patients' walking activity levels vary greatly. Walking strongly linked with TKA UHMWPE implant creep and distortion. UHMWPE creeps early post-implantation. Consider clinical wear and exercise. This disturbs prosthetic knee joints since younger, more active patients demand longer lifespans.(Ferber, R., & Osis, 2015).

CONCLUSION:

In conclusion, the examination of stress and tribological properties in relation to artificial human knee joints is a critical aspect of biomedical engineering and orthopedics. Understanding the mechanical stresses and tribological interactions in these artificial knee joints is crucial for improving their longevity and patient satisfaction. This study has highlighted several important findings and considerations.

Firstly, the stress analysis within artificial knee joints is essential to ensure their ability to withstand the complex mechanical forces they encounter during everyday activities. Proper stress analysis is crucial for preventing component failures and bone damage, ultimately leading to fewer revision surgeries.

Secondly, the study of tribological properties, including friction, wear, and lubrication, is vital for optimizing the performance and durability of artificial knee joints. Achieving low friction, minimal wear, and adequate lubrication is crucial for preventing complications and ensuring patient comfort.

The choice of materials for artificial knee joints is critical, with metal-polymer combinations being the most widely used due to their low friction and high wear resistance. Advances in materials and design have contributed to the success of knee replacement surgeries.

The advancements in technology, such as robotic-assisted knee replacement surgeries, have improved the precision and success rates of total knee replacements. These technologies have led to increased accuracy, quicker recoveries, and reduced complications.

It is important to note that the longevity of artificial knee joints can vary based on factors like patient-specific characteristics, activity levels, and the quality of surgical procedures. Understanding the complex interplay of biomechanics and wear is essential for enhancing the performance and durability of artificial knee joints.

The study of stress and tribological properties in artificial knee joints is a dynamic and multidisciplinary field that has significantly advanced the understanding and treatment of knee joint diseases and injuries. Continued research and innovation in this area are necessary to further improve the quality of life for patients who rely on artificial knee joints.

CONCFICT OF INTEREST: NO

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