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ORTHOBIOLOGIC AND ROBOTIC INNOVATIONS FOR TENDON-TO-BONE HEALING IN CHRONIC ROTATOR CUFF TEARS

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ABSTRACT

Chronic rotator cuff tears are a clinical challenge due to chronic inflammation, progressive tendon degeneration, impairment in regeneration and fatty infiltration. High retear rates, particularly in chronic and large tears, highlight the limitations of mechanical repair alone. These limitations highlight the need for methods that can solve the biomechanical stability and the biological deficits that compromise healing. Orthobiologics utilise allogeneic and autologous substances derived from human cells and tissues to promote pain relief, tissue healing and enhance functioning through anti inflammatory effect. Current strategies include platelet rich plasma injection, bone marrow aspiration injections and mesenchymal stem cell therapy. Biologic augmentation is aimed at improving clinical outcomes and healing rates in rotator cuff repair. Robotics enhances the effectiveness of biologic augmentation by creating a mechanically optimized environment for healing. Robotic and navigation-assisted technologies support improved surgical precision, anchor placement accuracy, footprint restoration, and control of tendon tension. Technologies like three-dimensional imaging and artificial intelligence allow targeted biologic release and customised surgical plans for each individual. Comparing preclinical studies and clinical outcomes remains inconsistent, largely due to variability in biologic preparation, patient related factors such as their chronic condition and tissue quality. In chronic rotator cuff repair, orthobiologics and robotics show an advanced approach in the clinical treatments. Future studies and clinical trials will be critical to confirm and proceed these advanced treatment goals.

SECTION 1 - INTRODUCTION

1.1 Burden of rotator cuff tears

Rotator cuff acts as a dynamic stabiliser of the glenohumeral joint by compressing the humeral head inside the glenoid cavity of the scapula and allows for axial rotation of the shoulder joint.[2]

Shoulder disorders are rapidly increasing worldwide and rotator cuff injuries are the most common pathologic condition in the middle aged and elderly population.

Rotator cuff injuries can range from tendinopathies to partial or complete tears. Ageing is commonly linked to the disorder, showing an approximately 62% increase in cases among patients aged 80 and above compared to the other age groups. Other risk factors include trauma, hypercholesterolemia, smoking, poor posture and family history. Occupation and activities involving overhead movements and overuse are among other common aetiologies.[3]

Rotator cuff tears present with pain and decline in shoulder mobility and strength. Functional disability often causes decline in quality of life. Patients with highest pain levels were reported to have the highest functional disability and lowest health related quality of life.[4]

Sleep disturbance is another common symptom reported in 85% of the patients affecting the quality of life.[5]

1.2 Biological challenges in tendon-to-bone healing

Degenerative tendinopathy starts as changes in the extracellular matrix of the tendons and small

inflammatory changes around the tendons. Chronic degenerative changes weaken the structure leading to partial tears. Under continued mechanical stress and insufficient healing, the partial tears, particularly those involving > 50% of the tendon progress into complete thickness tears.[6]

Chronic rotator cuff tear can lead to tear progression and tendon retraction developing rotator cuff arthropathy which is characterised by disorganised glenohumeral joint and migration of humeral head.

1.3 Rationale for combining orthobiologics and robotics

Despite the improvements in surgical interventions in the past decade rotator cuff arthropathy remains difficult to treat.[7] Chronic tears are associated with muscular atrophy and fatty infiltrations that can negatively impact the prognosis.[8]

Current strategies of treatment aim to manage pain and improve function. Conservative treatments include analgesics and physiotherapy. Low molecular weight sodium hyaluronate injections have shown results in pain management. They have similar effects to steroids in pain control but with a safer adverse effect profile.[9] Surgery is the preferred treatment for tears deemed irreparable.

Orthobiologics utilise allogeneic and autologous substances derived from human cells and tissues to promote pain relief, tissue healing and enhance functioning through anti-inflammatory effect. Current strategies include platelet rich plasma injection, bone marrow aspiration injections and mesenchymal stroll and stem cell therapy. Biologic augmentation is aimed at improving clinical outcomes and healing rates in rotator cuff repair.[10]

Decision making is crucial for surgical repair of irreparable tears, artificial intelligence has emerged as a valuable tool in the process. It has enhanced the interpretation of magnetic resonance imaging, improved surgical planning and enabled prediction of postoperative outcomes. Simplifying and personalising patient care. The capacity of AI to revolutionise patient care by improving the accuracy, efficiency and personalisation is promising but experimental.[11]

This literature review aims to critically analyse the current evidence on orthobiologics and robotic innovations for tendon-to-bone healing in chronic rotator cuff tears by examining their mechanisms, clinical effectiveness, limitations and future research directions.

2.1 Degenerative tissue changes and reduced healing potential in chronic rotator cuff tears

The rotator cuff comprises four muscles (supraspinatus, infraspinatus, teres minor, and subscapularis) and their tendons. Together, they help stabilize the shoulder joint and enable lifting and rotational movements.[12]

Tendon tears occur when a tendon pulls away from the arm bone, usually as a result of overuse or injury, causing an inability to use the arm properly.[12]

When a rotator cuff tear becomes long-standing (chronic), the tissues undergo changes that reduce their healing potential. These changes include:
Fatty infiltration, which occurs when muscle tissue is replaced by adipose tissue within the epimysium.[13] This results in degenerative muscle loss, and higher grades of fatty infiltration are associated with increased retear rates.

Bone and tendon quality also deteriorate. Reduced bone density (osteoporosis) weakens tendon attachment and increases stress at the bone-tendon interface.[14]

Hyperlipidemia alters the mechanical properties of tendons as lipids accumulate within the extracellular matrix (ECM).[15]

Smoking, a high-fat diet, and diabetes also contribute to poor healing. The longer the tear has been present, the poorer the tissue quality and the greater the risk of recurrent tearing.[16]

Sustained hyperglycemia significantly impairs bone-tendon healing by reducing fibrocartilage formation, collagen organization, and mechanical strength.[17]

Overall, these chronic changes worsen shoulder biomechanics by causing muscle weakness, tendon retraction, and fatty degeneration. They also reduce blood flow and the biological healing capacity, leading to poorer tissue quality.[18]

2.2 Chronic inflammation and reduced vascularity deteriorate tendon quality

In chronic rotator cuff tears, which are generally defined as tears persisting for more than 3 months, prolonged inflammation contributes to progressive tendon degeneration.

The role of inflammation in the pathogenesis of tendinopathy may not be clinically evident, particularly during the initial phase.[19]

However, inflammation persists in tendinopathic tissues and involves prolonged expression of pro-inflammatory cytokines such as IL-1β and TNF-α. These cytokines activate signaling pathways such as NF-κB, which upregulate the production of proteolytic enzymes, including matrix metalloproteinases (MMPs). MMPs degrade extracellular matrix (ECM) components, particularly structural collagen, which is essential for tendon strength. An imbalance between MMPs and their natural inhibitors (TIMPs) results in collagen disorganization and reduced mechanical integrity of the

tendon matrix.[20]

Tenocytes (tendon cells), when exposed to inflammatory signals, undergo phenotypic changes and produce catabolic factors, further compromising the surrounding tissue quality.[21]

In hypovascular regions of the tendon, persistent inflammation delays healing, creating a continuous cycle of degeneration and poor tendon quality. Diseased tendons also show disordered neovascularization.

However, this vascular growth does not indicate adequate perfusion; instead, it reflects pathological remodeling and an overall poor functional blood supply, further reducing oxygen and nutrient delivery, both of which are essential for tissue repair.[22]

2.3 Failed enthesis regeneration

Chronic tendon tears frequently fail to recreate the native enthesis. The normal tendon-to-bone interface, including the zones of mineralized and unmineralized fibrocartilage, is not regenerated during healing.[23]

Following injury and surgical repair, healing usually results in fibrovascular scar tissue, producing an interface that lacks the normal composition, organized collagen structure, and mineralization required for effective load transfer and mechanical strength.[24]

This biomechanical mismatch, caused by differences in strength and structure, makes the repaired tendon more susceptible to failure and recurrent tearing. Standard suture-based repair techniques reconnect the tendon to the bone but do not stimulate the complex cellular differentiation required for enthesis regeneration. As a result, the repaired interface has poorer mechanical properties than the native tendon-to-bone attachment.

Section 3

3.1 Biology of Tendon to Bone Healing Native Enthesis Structure

The rotator cuff enthesis is a fibrocartilaginous insertion that connects tendons to bone through four compositional zones which are dense fibrous tendon, uncalcified fibrocartilage, mineralized fibrocartilage and bone.[25,26] This graded structure makes a continuous stiffness gradient that smoothens transfer of load i.e. collagen fibers and proteoglycans gradually transition to calcified matrix so that the stress concentrations at the junction are minimized.[27,25] In other words, the enthesis functions as a buffer between soft and hard tissues with its tidemark (boundary of calcified and uncalcified fibrocartilage) marking the boundary between soft and hard tissues.[27,25] This zonal organization is very essential for normal biomechanics for example, the unmineralized fibrocartilage layer dissipates bending forces acting on the tendon and the tidemark further ensures elastic compliance before bone attachment.[25,27]

3.2 Fibrocartilage Formation Phases

During tendon repair, the native fibrocartilage seldom regenerates. Instead, healing proceeds through the classic wound healing phases.[28,29] Inflammatory phase (1 week long), during this phase a hematoma forms at the repair site and neutrophils/macrophages infiltrate to clear debris and release cytokine such as tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β) and interleukin-6 (IL-6).[28,29]

Proliferative phase (2-3 week long), fibroblasts proliferate and deposit granulation matrix (mostly type III collagen).[28] Remodeling/Maturation (3-26 week long), collagen type III is gradually replaced by type I collagen and fibers reorient themselves. In healing of rotator cuffs, fibroblasts form a fibrous scar layer between tendons and bone rather than true fibrocartilage.[28,29] This scar tissue lacks the graded fibrocartilage zones, so it has inferior mechanical properties and therefore repaired cuffs rarely regain the native enthesis structure.[28,29]

3.3 Factors Impairing Biological Healing

Several patient and biomechanical factors impair the enthesis healing process. (i) Chronicity, it includes long-standing (chronic) tears leading to tendon retraction, muscle atrophy, fatty degeneration and increased repair tension and such chronic changes worsen outcomes.[30] (ii) Age, older patients show poorer healing together with age-related degeneration of tendon and bone (reduced cell responsiveness and diminished blood supply) correlates with higher failure rates.[3031] (iii) Inflammation, is a protracted or excessive inflammatory milieu (as seen in metabolic diseases like diabetes/obesity) which skews macrophages to a persistently pro-inflammatory (M1) phenotype, thus promoting fibrosis over regeneration and disrupting matrix formation.[31,29] (iv) Hypoxia, the native enthesis, is relatively avascular and has insufficient oxygen delivery in the healing interface which impairs cellular survival and matrix synthesis.[29,31] (v) Mechanical overload, early or excessive loading can exceed the weak repair and conversely, the complete unloading also hinders fibrocartilage formation. Animal studies show controlled loading is best because immobilization improved early tissue organization, but delayed (graded) loading produced superior strength and improved matrix quality compared to immediate heavy motion.[25] So, chronic degeneration, patient age, unresolved inflammation, hypoxia, and improper mechanical stress all impede the regenerative process at the tendon to bone interface.[29,30]

SECTION -4. Current Surgical Approaches

4.1 Arthroscopic repair techniques

Arthroscopic repair of the rotator cuff can be done by a single row or two rows suture. Several randomized trials and meta-analyses have been used to evaluate these methods. In general, the two approaches cause nearly the same improvement in clinical outcomes, including pain

relief and functional scores.[32,33] However, the double-row repairs are more comprehensive in covering the footprint and bring in more structural integrity. As an example, a study by Millett et al. was able to show a much lower re-tear rate with double-row repairs (14.2%) versus single-row repair (25.9%), although the scores on shoulder were similar.[32] Similarly, Wang et al. discovered that double-row constructs provide better tendon strength and range of motion of the shoulder in case of massive tears, as well as fewer re-tears as compared to single-row repairs.[33] Single-row complex and equivalent procedures have been proposed in lieu of the biomechanics of double-row repairs to recreate the complexities of transosseous. A meta-analysis performed recently showed that there was no significant difference in any outcome measure between complex single-row and true double-row repairs (TOE).[34] In general, both methods have similar clinical benefits, although the double-row fixation seems to be biomechanically superior (has increased load to failure and decreased proportions of gap formation), and there-tear rates are lower.[32,34]

4.2 Limitations in chronic large tears

The process of healing in chronic and extensive tears of the rotator cuff is hampered due to high tissue degeneration. Tendon retraction (it is often possible to see it beyond the glenoid rim) is a common phenomenon with massive tears, making it difficult to reattach the tendon to the bone[42] The tendons which are retracted have structural changes (reduced length of fibres, altered pennation) which facilitate the fatty degeneration of the muscle belly.[36] Therefore, severe muscle degeneration and lipid permeation are good predictors of repair failure. It has been found that shoulders with increased Goutallier fatty infiltration scores (i.e. >Grade 2) have a much higher rate of retear - around 60% - after repair.[36,37] The size of the tear per se is linked to more significant fatty infiltration of muscle; an enlargement of supraspinatus-infraspinatus tear size was related to higher fat grades in all rotator cuff muscles[35] Finally, chronic large tears are a combination of several factors - the shortening of the length of tendons, the development of severe muscle atrophy, and the alteration of fatty layers - which are obstacles to healing. Overtraction and fatty degeneration produces a significant weakening effect on the tendon-muscle unit making tendon-to-bone healing unlikely.[36,37]

Goutallier Classification of Fatty Infiltration

Stage 0: Normal muscle which is not fat-infiltrated. Volume and architecture of the muscles are maintained.

Stage 1: Internality of a few fatty streaks in the muscle. The bulk of muscles is basically normal.

Stage 2: Fat which is not dominant (<50% fat) but still has fat. The onset of muscle degeneration is early but repair can also be successful.

Stage 3: The body contains fats and muscle tissue that exist in relatively equal measure (50/50). Serious degeneration and lower healing capabilities.

Stage 4: The fatty tissue is more than the muscle (>50% fat). Extensive muscle atrophy and extremely high chances of retear and failure of repair.

5 ORTHOBIOLOGICS FOR ROTATOR CUFF REPAIR

5.1. PLATELET-RICH PLASMA (PRP)

Rotator cuff repair continues to be challenged by limited biological healing at the tendon–bone interface, contributing to the risk of structural failure after repair. These challenges have encouraged increasing interest in orthobiologic augmentation strategies, particularly platelet-rich plasma (PRP), which aims to improve the local biological environment through the delivery of platelet-derived growth factors involved in tendon healing. Although early clinical studies have shown biological results, clinical benefits remained inconsistent. Postoperative shoulder function improved in both PRP and control groups, but PRP inconsistently outperformed functional or structural superiority over standard repair.[38]

PRP promotes angiogenesis by increasing VEGF. The neovascularisation ensures increased oxygen and nutrient supply to the damaged site and helps in establishing an ideal environment for repair.[39]

In recent clinical studies, PRP's formulation and its transfer at the reconstruction site have shown positive results. Thrombin-activated PRP gel injected into the tendon-bone interface area via arthroscopic technique showed better structural regeneration, functional improvement, and post-surgery pain alleviation. The healing of the tendon and increase in tendon thickness in the PRP group were confirmed in an imaging-based study. However, there is a lack of evidence on the effectiveness of PRP gel in the long term because of limitations in the study.[40]

PRP-loaded hydrogel constructs have been investigated to improve the regeneration of the tendon-bone interface using the mechanical properties of the biomaterial scaffolds along with the biological effect of the PRP. In a rat rotator cuff repair model, a PRP-loaded carboxymethyl chitosan–tannic acid hydrogel promoted osteogenic differentiation and tendon-related collagen I expression, while showing good biocompatibility and prolonged growth-factor release. The hydrogel improved the tendon-bone interface, bone remodeling and strength, demonstrating a bioactive technique for improved healing.[41]

Despite being easily available clinically, the routine use of PRP has been highly debatable due to inconsistencies caused by differences in the amount of platelets, leukocytes, activation and delivery mechanisms that are involved.[42]

5.2. MESENCHYMAL STEM CELLS (MSCs)

Mesenchymal stem cells have emerged as a promising

biological therapy for rotator cuff repair, as they have the ability to alter the biological environment of the tendon healing rather than providing only symptomatic relief. Rotator cuff tears are associated with tendon degeneration, fatty infiltrates, chronic inflammatory processes, and limited healing potential, resulting in the poor efficacy of surgical treatment.[43] MSCs can be isolated from bone marrow, fat, or umbilical cord tissues. Therapeutic actions of MSCs are primarily based on their paracrine effects and secretion of cytokines, growth factors, extracellular vesicles, and microRNAs, which might lead to reduced inflammation, enhanced angiogenesis, and extracellular matrix remodeling.[43,45]

In animal studies, MSCs controlled the gene expression responsible for tendon development, allowed tissue remodeling, and helped to improve the biomechanical properties of healed tendon tissues.[43,45,46] The exosomes secreted from MSCs helped to promote angiogenesis and inflammation modulation through M1 macrophage phenotypic inhibition, and improved tendon-to-bone repair and biomechanics.[45] In addition, MSCs isolated from the umbilical cord were freeze-tolerant, and enhanced healing and biomechanical parameters of the rotator cuff injury in rats.[46]

Moreover, the combination of MSCs with PRP will have more benefits since this will improve the viability of the MSCs, provide an anti-apoptotic effect, and produce angiogenic and osteogenic growth factors like VEGF, PDGF, and FGF-2.[44] In animal studies, combined MSC-PRP therapy results in superior tendon-bone interface and improved mechanical strength, suggesting synergistic biological interaction.[44]

Recent clinical studies suggest MSC augmentation is not related to an incidence of adverse effects. For long-term safety, cell source, dosage and efficacy, larger randomised trials with follow-up are required.[47]

Even though MSC therapy has been promising in terms of regenerative properties as well as low toxicity, the use of this therapy is currently hindered by high costs of preparation, regulatory issues and the absence of standardized treatment protocols.[42]

5.3 GROWTH FACTORS (FGF-2, TGF-B, BMP-12)

Fibroblast growth factor-2 (FGF-2) stimulates tenogenic progenitor cells and enhances tendon-to-bone healing in rotator cuff injury. In a rat model, local application of FGF-2 at the repair site has increased proliferation (as indicated by PCNA-positive cells) and the number of MSCs. Expression of Scleraxis (Scx) from 4 to 8 weeks shows tenogenic differentiation, while tenomodulin (Tnmd) from 4 to 12 weeks reflects tendon maturation. FGF-2-treated tendons showed more collagen fibers and improved tensile strength.[48]

The transforming growth factor-beta (TGF-β) is involved in a wide range of actions related to tendon repair through fibroblasts' proliferation, migration, and collagen synthesis through Smad-dependent and non-Smad signaling pathways. TGF-β facilitates tenogenesis and early matrix deposition and induces myofibroblast formation, fibrosis, and adhesion. Thus, TGF-β acts as a growth factor that can regenerate and promote fibrosis in tendons; therefore, there is a need for temporal modulation in rotator cuff tendon repair.[49]

BMP-12 induces tenogenic differentiation in human adipose-derived mesenchymal stem cells by regulating tendon-specific transcription factors, scleraxis (SCX) and Mohawk (MKX), and enhances collagen type I expression and tendon matrix formation. BMP-12 changes the secretory and immunomodulatory functions and suggesting therapeutic effects may depend on the controlled delivery and its cellular environment.[50]

The major portion of evidence on the use of these growth factors is based on preclinical experiments, and additional clinical research is necessary to identify proper dosages, timings and delivery methods before using the method clinically.[42]

5.4 SCAFFOLDS AND PATCHES

A bioactive collagen scaffold (BCS) is prepared from highly purified type-I collagen; it is virtually DNA-free, negative for porcine α-Gal epitopes, and has low immunogenicity. In vitro, human tendon-derived cells, which are cultured on BCS, showed increased proliferation, alignment, and upregulation of tendon-specific markers (TNMD, Ten-C, Mohawk, and Col-1 α1). Safety and feasibility were demonstrated in the pilot clinical study; MRI at 12 months showed complete healing in 64.8% of the patients, along with improved functional outcomes, reduced pain, and better quality of life.[51]

Rotator cuff repair failures are high, particularly for large tears, due to slow healing at the tendon-bone interface. Rotium Wick is a synthetic, bioresorbable interpositional nanofiber scaffold intended to be placed at the tendon-bone interface. Its nanofibrous structure has been shown to support cell proliferation and ingrowth and has been associated with the regeneration of Sharpey-like fibers in preclinical studies.[52]

Both scaffold and patch augmentation enhance healing by providing mechanical relief to the injured tendon during the initial period of healing. In addition, they serve as an extracellular matrix-like structure for the recruitment of cells and integration of tissues along with formation of collagen and tendon-to-bone interface regeneration.[53]

Biologic scaffolds are commercially available for the repair of rotator cuffs and are potentially cost-effective in some cases.[42]

Section 6 -Limitations of Orthobiologics in Chronic Tears

6.1 Heterogeneous Results in Large Tears

In this regard, many biological modalities such as platelet-rich plasma (PRP), scaffolds, and mesenchymal stem cells (MSCs) help reduce retear risks. Multiple research studies (randomized controlled trials and meta analyses) have suggested that PRP has reduced the rotator cuff retear rate. Larger rotator cuff tears are always problematic in the future and have a high risk of retear.Bone marrow-derived stem cells added to synthetic scaffolds show promise for both mechanical stability and biological response induction. superior capsule reconstruction, an interposition graft in which the upper joint lining of the shoulder is rebuilt using either your own (autograft) or donor (allograft) tissue. Tendon repair is enhanced by stem cells generated from adipose tissue and bone marrow but as of now PRP and stem cells are not widely used because there have been many trails in peer review stage which is highly needed to study about outcomes.[54] Due to the considerable variation in their clinical manifestations, the varying chronicity of the disease, and the absence of conventional therapeutic techniques, tendenopathies can be difficult to treat. These elements may affect the healing process and make it hard to evaluate clinical results.[55]

6.2 Delivery, retention, and integration issues

One big barrier with biological augmentation is not just what is administered to the patient, but also how well it adheres to and incorporates at the tendon-bone contact, which is crucial for the repair of chronic tears. Due to the intricate enthesis design, poor vascularity, and mechanical forces that interfere with biologic retention during the early stages of healing, tendon-bone integration is infamously challenging.

After a certain amount of time, orthobiologic agents like PRP and STEM cells may diffuse away from the healing site, decreasing their efficient concentration and duration of impact at the crucial interface. The mechanical circumstances surrounding tendon repairs is the cause of this issue. Even little movements like passive motion, muscle tension, early rehabilitation, and typical pressures can cause mechanical strain at the repair site when a tendon is repaired since the area is not fully healed. When injectable orthobiologics (such as PRP, stem cells, or growth factors) are injected as a liquid without being fastened to a scaffold or carrier, they can readily leak out, spread out, or be washed out by joint fluids (synovial fluids) and blood flow. are forced by loading forces or movement out of the desired region. Consequently, the biologic substance does not remain at the required location long enough to affect healing.[56] Integrating with the native tissue is uncertain, even if biologics agents stay at the interface. Particularly in big or major tears, chronic tears result in the formation of scar tissue, inadequate blood flow, and deteriorated enthesis structure that restricts cell engraftment and matrix remodeling. This could reduce orthobiologics' potential regeneration benefits, leading to inconsistent clinical outcomes and encouraging preclinical evidence. Ultimately, for greater results, we should wait for numerous future improvements in research on targeted delivery strategies, scaffolds that improve retention, and a deeper comprehension of the tendon-to-bone healing milieu.[57]

SECTION 7- Robotics in Shoulder Surgery

Robotics in shoulder arthroscopic surgeries is more important than ever before because of the growing demand for better and more precise techniques. Robotic-assisted shoulder surgeries are predominantly used in total shoulder arthroplasty (TSA) and reverse shoulder arthroplasty (RSA), which are particularly indicated for patients with end-stage osteoarthritis and rotator cuff deficiencies. This requires utmost precision in glenoid component placement and positioning.[60]

Although robotic systems were developed primarily for shoulder arthroplasty, the advancement in implant placement, navigation, and guidance is highly relevant to arthroscopic shoulder surgeries. In arthroscopic rotator cuff repair, the placement of suture anchors, recreation of the original tendon attachment site, and the correct tendon tension are all important factors in the repair's integrity, biomechanical stability, and healing potential.[58,67] The precise placement of the glenoid baseplate and glenosphere, which is made possible by the development of robotics in the orthopaedic sector, is an essential component of traditional shoulder arthroplasties.[61]

Robotics is primarily utilised in shoulder replacement procedures; its use remains limited in soft tissue repairs, such as rotator cuff repairs, and is currently in the phase of clinical studies.[58]

Some Robotics systems widely used for Shoulder arthroplasty are;

1. **Zimmer Biomet - ROSA® Shoulder System** — a **robot-assisted surgical assistant** designed specifically for shoulder replacement (both TSA and RSA), provides accurate and precise glenoid and humeral placement, which is a **Precarious** part of shoulder surgery. The recently developed SignatureTM ONE Surgical Planning System 2.0, which employs a 3-D image-based method for visualisation, surgical planning, and patient-specific guide development, is integrated with ROSA Shoulder before surgery.[59]

2. **Mako System (Stryker):** The Mako system utilises haptic technology and real-time guidance to ensure that implant components are positioned precisely as intended during surgery, thereby protecting surrounding tissue and bone[65] Because it needs exact alignment for stability and range of motion, this technology is particularly useful in RSA.[63]

We have a few other companies that have shown significant development in the use of augmented reality in shoulder arthroplasty, such as **NextAR™**, an **augmented reality (AR)-based surgical platform** developed by **Medacta International,** which is a computer-assisted navigation and augmented reality guidance system that lets surgeons see and match pre-planned implant placement to actual intraoperative anatomy[64] **ExactechGPS® Shoulder,** which provides 3D CT navigation and real-time guidance for glenoid placement for TSA and RSA,[65] and **NaviPro® Shoulder** by **Kinamed Navigation Systems** provide image-free shoulder navigation.[66]

While some progress has been made in robotic shoulder surgery, it is not widely used in rotator cuff repair. Currently, there is little evidence supporting the use of robots in arthroscopic rotator cuff repair, and they are primarily designed for shoulder arthroplasty. Future research should determine whether robotic assistance improves placement of anchors, tensioning of tendons, repair integrity, and outcomes, and evaluate its cost-effectiveness and integration with biologic augmentation.[58,62,68]

SECTION -8. Robotics-Enhanced Biological Healing

The application of AI and robots has set new standards for the provision of healthcare. By increasing accessibility, accuracy, and customisation, it offers greater clinical advantages. Patients are increasingly receptive to robots in minimally invasive operations since they are safer, more accurate, and need less recovery time than open surgery. AI improves these advancements and provides patients with individualized treatment regimens, expanding access to care even in developing regions.[69]

Robots for surgery can have broader advantages in other surgical procedures, such as skin flaps, where they shorten the time needed to collect tissue in tumor situations. In treatments like microvascular anastomosis, tumor radical surgery, tissue repair, tendon fixation, etc., the use of surgical robots can provide favorable outcomes and decrease the incidence of problems.[70] sophisticated 3D printing methods to create bioactive, cell-free, anatomically precise scaffolds that closely mimic the mechanical gradients and heterogeneous microstructure of the natural TMJ disc. Micro-precise spatiotemporal delivery, which enables regulated distribution of bioactive cues across several scaffold regions to match natural tissue architecture, was a novel breakthrough. When it comes to shoulder restoration, cell-free scaffolds are especially important since they can promote healing without raising immunologic risk. Therefore, bioactive 3D-printed scaffolds that are mechanically and anatomically graded, along with in vivo degradation monitoring, may significantly enhance biologic integration and functional results in shoulder tendon replacement.[71] Compared to conventional linear stretch, advanced robotic systems capable of applying multiaxial and physiologic mechanical stimulation are more likely to promote tenogenic (tendon-like) cell development and integration of biologics into scaffolds. Robotic systems can increase the mechanical integrity and robustness of biologic scaffolds, improve cell differentiation and ECM quality, and improve matrix deposition and alignment. These developments may increase the reproducibility and therapeutic viability of biologic medicines with regulated delivery, such as MSCs, growth factors, and scaffold cues.[72] Over the past few decades, medical robotics has changed dramatically as hospital robots systems have grown in number. High accuracy, increased surgeon dexterity, 3-dimensional imaging capabilities, and the possibility of telesurgery are all benefits of robots in the medical profession. Given the surgeon's limited view of the surgical workspace during minimally invasive procedures, a variety of medical imaging modalities, including computed tomography, magnetic resonance imaging, ultrasound, and X-ray, can provide significant visual information needed for pre- and intraoperative planning and guidance. This is especially crucial for robotic surgery.[73]

Section 9

9.1 Robotics in Rehabilitation

Robotic Exoskeleton-Assisted Passive Motion

Early gentle, passive and non-vigorous mobilization of a repaired rotator cuff is desirable to prevent tendon stiffness and adhesions but patients must avoid overloading the repair. Robotic exoskeletons can provide very precise and passive motion assistance and the robot drives the patient’s arm through controlled ranges without active muscle effort.[74,28] By automatically limiting the joint angles and torques, a robotic shoulder orthosis can help ensure that mobilization stays within the safe thresholds. For example, gravity compensating devices (like the WREX system) have been shown to offset arm weight and reduce load on shoulder muscles during movement.[75] Such systems enable consistent and repeatable passive exercises under supervision.

Commercially developed rehabilitation robots range in price from roughly **$9,000** up to **$100,000**, high unit cost and limited production mean these devices have slow market penetration.[77] Most importantly, clinical and animal data suggest that early controlled motion does not harm tendon to bone healing as one study notes that early passive range of motion does not negatively impact repair strength and conversely, can improve collagen fiber organization.[28] Thus, exoskeletal assistive devices allow initiation of safe passive therapy soon after surgery and preserve the mobility of the patient while safeguarding the repair.[28,75]

9.2 Controlled Loading for Fibrocartilage Maturation

Once the initial repair has started, gradual loading can stimulate fibrocartilaginous remodeling of the enthesis. Tendon to bone tissues are mechanosensitive and

appropriate loading promotes proper maturation of the matrix.[76,25] Current rehabilitation protocols emphasize more on early controlled eccentric loading for tendons to improve the healing outcomes.[76] In the animal models of rotator cuff repair we have noted that excessively early or complete unloading was suboptimal i.e. one study found that a brief period of immobilization then followed by a delayed loading yielded better collagen alignment and mechanical properties than either immediate motion or prolonged immobilization[25] This study suggests that after an initial phase of resting, gradually increasing the tension (e.g. gentle resistance exercises progressing to active motion) enhances tissue organization. Also, increasing mineral and collagen density in the healing interface with time helps form a functional fibrocartilage layer.[25,76] In practice, controlled mobilization protocols (often supervised by therapists) progressively load the repaired tendon to encourage fibrocartilage deposition and strengthening, therefore improving the enthesis's mechanical integration.[76,25]

SECTION -10. Emerging Technologies Combining Robotics + Biologics

Artificial intelligence(AI)-driven biologic healing has been gaining importance across different fields of orthopaedics. It forecasts complications like nonunion, implant failure, infection, and soft-tissue retear. Machine learning models use patient-specific decision-making tools, comorbidities, injury characteristics, imaging features, surgical variables, and rehabilitation data, etc

Several studies have investigated the application of AI and machine learning algorithms to comprehend and forecast the recurrence rates of extremely common conditions, such as shoulder dislocations after Bankart repair in Van Spanning et al. (2022) and estimating the likelihood of a retear after rotator cuff tear repair surgery in Allaart et al.(2023) emphasising the potential of AI to support individualised clinical decision-making rather than replace surgical competence.[78,79]

The merging of AI with regenerative medicine is also being investigated. AI-assisted three-dimensional (3D) bioprinting has shown promise in fabricating tendon-like scaffolds with controlled architecture for tendon tissue engineering; however, these technologies remain in the preclinical stage, and additional in vivo and clinical studies are required before translation into routine orthopaedic practice.[80]

Artificial intelligence (AI) has shown promise in the diagnosis and treatment of rotator cuff tears. It has improved diagnostic consistency, supported preoperative evaluation of tendon morphology, muscle quality, and surgical planning, and demonstrated excellent diagnostic accuracy in identifying and classifying rotator cuff tears on magnetic resonance imaging (MRI) and ultrasound. Additionally, machine learning models have been created to forecast structural failure after rotator cuff repair, allowing for outcome prediction and patient-specific risk assessment.

Before being routinely used in clinical settings, the majority of these models are still in the investigational stage and need additional external validation.[82,83]

The SuPer framework, created by Li et al. and implemented on the da Vinci Surgical System, allows for three-dimensional mapping of deformable soft tissue and real-time tracking of surgical instruments during endoscopic surgery. This technology offers a basis for future research into robotic-assisted tissue assessment and surgical guidance, even though it hasn't been tested in rotator cuff repair.[81]

Future developments in shoulder surgery and rotator cuff repair may benefit from advancements in surgical perception, even though robotic-assisted tissue quality assessment has not yet been established in these fields. The majority of AI models are still exploratory and lack external validation, which restricts their current clinical applicability despite promising results.

SECTION -11. Future Directions

11.1 Personalized biologic + robotic pathways

New solutions are aimed at both biologic treatment and robotic precision customization of the approaches to the specifics of the patient.

Biomarkers and patient profiling are used in precision orthobiologics, which personalizes the dosage of regenerative therapies,[81,88] Through the example of thorough tissue and inflammation screening, medical practitioners can select the most optimal orthobiologic agent and dosage of each particular tear.[81] The ultimate goal is to attain truly personalized interventions - to be able to administer the correct biologic to the correct patient at the correct time.[81,88] At the same time, robotics provides patient-centered surgery. The current advanced robotic technology integrates preoperative 3D imaging with intraoperative guidance to customize positioning of implants or grafts to anatomy of a patient.[82] Individual instrumentation and instant feedback increases accuracy of alignment and fixation.[82] Combined, the advances allow surgeons to modify biologic dosages and precision in surgery.[82,86] As an example, 3D-printed tendon patches or scaffolds (as a PLGA scaffold laced with stem cells) can be robotically delivered on a personalized basis to a large tear, improving tendon-to-bone healing.[86] Biologic patches can also be resorbable scaffolds, which redistribute forces and help to integrate tissues.[87] To conclude, the future trends will also group patients according to the tear details and feed patient-specific orthobiologics using robotics to provide optimal location.[81,88,89]

11.2 Automated biologic augmentation

In the future, fully automated systems may enforce biological grafts and agents to be implemented without

necessarily having a surgeon on the ground.[89,90] Studies are looking at nanorobotic systems that could potentially provide regenerative factors at a cellular level on its own.[90] As an example, hypothetically, the so-called AI-controlled nanorobots could detect microdamage in tendon tissue and inject growth factors or cells in the correct location precisely where the tissue requires it.[90]

Similarly, researchers predict robotic intelligent platforms that would be able to print and implant tailor-made grafts.[89,91] The adoption of AI, 3D printing and sensor feedback would allow a robot to manually make a tendon scaffold and insert it into a patient. Simultaneously, machine learning models can help to identify regenerative needs of each patient by analyzing a range of factors (age, tear chronicity, muscle quality) to predict a healing process.[88] In fact, the mass trend of automation is stimulating the creation of the so-called fully automated orthopedic treatments combining AI, bioprinting, and robotics into single units.[88,89,90] Robots can also be developed as complex bioreactors: musculoskeletal humanoid robots have been shown to be able to subject engineered tendon constructs to cyclical loading in physiological patterns to improve tendon remodeling.[91] Overall, it is intended to develop an independent platform that would not only form but also deliver biological solutions - cell-seeded patches to growth-factor infusions - with exceptional precision through AI predictions.[88,89,90]

CONCLUSION

Chronic rotator cuff tears represent a significant clinical problem due to persistent inflammation, degenerative changes in tendons, fatty infiltration, poor vascularity, and inability to regenerate enthesis, which limit the healing capacity biologically and lead to high retear rates following repair. Even though there are advances in the field of surgical technology, restoration of a strong tendon-to-bone integration still represents an issue. Recent developments in robotic and navigational technologies might be helpful to increase the precision of surgery, provide an optimal anchor positioning, control the level of tendon tension, and conduct rehabilitation in a controlled way, thus creating a favorable mechanical environment for healing. Simultaneously, orthobiologic treatments such as platelet-rich plasma, mesenchymal stem cells, growth factors, and bioactive scaffolds aim at tendon-to-bone regeneration through anti-inflammatory action, angiogenesis and tenogenic differentiation, and extracellular matrix remodeling. Although the results obtained during preclinical investigations are promising, outcomes on the clinical level show variability due to different biologic formulations, application techniques, patient population, and research methodology used. Nevertheless, integrating biological augmentation with advanced surgical technologies represents a promising strategy for improving rotator cuff repair.

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