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Bone fixation techniques for managing joint disorders and injuries: A review study

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ABSTRACT

The majority of surgical procedures treating joint disorders require a technique to realize a firm implant-to-tissue and/or a tissue-to-tissue fixation. Fixation methods have direct effects on survival, performance and integration of orthopedic implants This review paper gives an overview of novel fixation techniques that have been evaluated and optimized for orthopaedic joint implants and could be alternatives for traditional implant fixation techniques or inspirations for future design of joint implantation procedures.

Method: The articles were selected using the Scopus search engine. Key words referring to traditional fixation methods have been excluded to find potential innovative fixation techniques. In order to review the recent anchorage systems, only articles that been published during the period of 2010–2020 have been included.

Results: A total of 57 studies were analyzed. The result revealed that three main fixation principles are being employed: using mechanical interlockings, employing adhesives, and performing tissue-bonding strategies.

Conclusion: The development of fixation techniques demonstrates a transformation from the general anchoring tools like K-wires toward application-specific designs. Several new methods have been designed and evaluated, which highlight encouraging results as described in this review. It seems that mechanical fixations provide the strongest anchorage. Employing (bio)-adhesives as fixation tool could revolutionize the field of orthopedic surgery. However, the adhesives must be improved and optimized to meet the requirements of an anchorage system. Long-term fixation might be formed by tissue ingrowth approaches which showed promising results. In most cases further clinical studies are required to explore their outputs in clinical applications.

1. Introduction

Injuries related to the musculoskeletal system comprise at least two-thirds of all significant traumas (Textbook of Disorders an, 2020). Joint injuries and inflammatory and degenerative disorders of joints make up the majority of common musculoskeletal disorders. Joint injuries refer to both bone and soft tissue complications at joints. The most commonly reported joint complications are osteoarthritis, tendinitis, rheumatoid arthritis, carpal tunnel syndrome, and bone fracture (Textbook of Disorders an, 2020). Frequently, open or minimal-invasive surgical procedures are required to treat and fix severe joint disorders.

A wide range of effective procedures to treat joint complications involve implant-based surgeries. Diverse types of implants have been utilized for decades in joint disorders treatments. Typically, their main function is to restore the affected bones and joints from trauma, arthrosis and other abnormalities. Additionally, osteochondral scaffolds have recently been developed to address cartilage lesions, which have great impact on society. Major implant applications can be categorized into (i) reconstructive joint replacements, (ii) spinal implants, (iii) orthobiologics and (iv) trauma joint implants (Filardo et al., 2014a). The clinical need for all of these categories is anticipated to increase in the foreseeable future, due to a worldwide rise of the ageing population, changes in lifestyle toward a more dynamic one, and higher expectations of quality of life in older age groups (Wang et al., 2011). Therefore, implants' performance and outcome need to improve in order to enhance implant integration, long-term stability and survival.

Success in the application of an orthopedic joint implant depends on multiple factors. Implant design, surface configuration, fixation method and surgical procedure play critical roles to decrease the failure rate of implantation. An insufficient fixation technique may cause serious issues

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such as movement, delamination, deformation and detachment of an implant which leads to failure of the implant and thus the requirement for additional treatment (Filardo et al., 2014a). The resulting revision surgery is often complex, has a relatively high failure rate and is expensive (Filardo et al., 2014a).

An improved fixation method could often positively affect the survival and integration of the implant. The main task of the fixation technique is to diminish migration of implant and to ensure short- and long-term integration of implant and body. Designing fixation systems that *are less invasive* could bring advantages to new implantations and improve the traditional surgical procedures.

Researchers and surgeons continuously develop novel fixation techniques in order to address clinical complications, to reduce the morbidity of surrounding tissues, and to improve the success rate of surgical procedures. An understanding of the novel fixation techniques, their successes and their complications is a basis for the improvement of the fixation of current and new implants utilizing in joint disorder treatments. This review paper gives an overview of novel fixation techniques that have been evaluated and optimized for orthopaedic joint implants and could be alternatives for traditional implant fixation techniques.

2. Method

The articles were selected using Scopus. To find recent innovative fixation techniques which brought advantages with respect to their preceding traditional alternative, words that refer to traditional fixation methods including screws, cement (traditional bone cements mainly act as filler for press-fit implants), reduction, plate, and replacement, were excluded. As a result, the main search thread was (fix* AND bone AND implant* AND joint AND NOT screw AND NOT cement AND NOT external AND NOT reduction AND NOT plate AND NOT replacement) with a filter on publication date to consider articles published between 2010 and 2020. The title-abstract screening was performed by one reviewer. Only English articles were included and simulation studies were excluded.

3. Results

Using the defined search threads, 425 articles were retrieved. After applying the selection and exclusion criteria 57 articles remained to be reviewed; 23 pre-clinical studies including *in vitro* and/or *in vivo* assessments on cadaveric human and animals, 15 retrospective studies, 6 case reports and technical notes, 4 descriptive studies, 4 prospective studies, 2 pilot studies, 2 systematic reviews, and 1 observational study. The fixation method(s), main achieved results, type of research study and application of each fixation technique have been extracted from the selected articles and presented in Table 1, categorized according to three main fixation principles that were derived: mechanical fixation techniques; tissue-ingrowth techniques; (bio-)adhesives.

3.1. Mechanical fixation techniques

The majority of applications included mechanical fixations which can be characterized in six categories: sutures (Fig. 1A), expanding implants (Fig. 1B), suture-buttons (Fig. 1C), pins (Fig. 1D), rods (Fig. 1E), and suture-anchors (Fig. 1F).

3.1.1. Sutures

Sutures (Fig. 1A) have shown promising results in a wide range of applications. These applications include: (i) soft tissue to soft tissue fixation, (ii) synthetic scaffold or allograft to bone fixation, and (iii) bone to bone fixation. Implantation of sutures results in firm anchorage of implant to both bone and soft tissue (Noyes and Barber-Westin, 2014). Various types of sutures have been reported, including: trans-osseous sutures (Merkely et al., 2019) (Chen et al., 2013), bone tissue suturing and soft tissue suturing (Noyes and Barber-Westin, 2014).

According to the evaluation of Merkely et al., the addition of trans-osseous sutures to the tibia results in stronger fixation and reduces the meniscal extrusion which should be considered for future arthroscopic MAT techniques (Merkely et al., 2019). Chen et al. evaluated a metal-free technique utilizing a trans-osseous suturing method to fix the patellar fracture. They reported lower invasiveness and a lower complication rate using trans-osseous suturing (Chen et al., 2013). Moreover, newly described surgical methods such as bone bridge or bone tunnel technique (Said et al., 2014) (Bariéet al., 2018) and basket weave technique (Fig. 3) are considered as soft tissue fixation which utilize sutures (Kodkani and Joshi, 2012).

Sutures have shown sufficient anchorage and superior outcome compared to fibrin glue for attachment of cartilage scaffolds in a biomechanical cadaveric study (Cassar-Gheiti et al., 2015). However, Bauer *et al* reported that even augmentation of fibrin glue and suture resulted in insufficient fixation of grafts considering prospective clinical and follow-up data of 18 patients up to 5 years (Baueret al., 2012). In addition, sutures can cause extra damange to the tissue (Kuang et al., 2019).

3.1.2. Expanding-implants

Expanding implants like the X-Fuse® and Smart-Toe® (Fig. 1B) system are utilized for bone to bone fixation, particularly hammertoe correction and fusion of small bones. They are made of Nitinol, which is a temperature-activated shape memory alloy. They recover their shapes after implantation to conform to patient anatomy. X-Fuse® and Smart-Toe® have been compared to their traditional alternative, K-wires, in multiple studies. In a biomechanical human cadaveric study (Rothermel et al., 2019), K-wires turned out to be superior since they could provide stiffer and stronger constructs in extension bending compared to the X-Fuse® and Smart-Toe® when applied for the correction of proximal interphalangeal arthrodesis of lesser toes. In a retrospective study in which 28 patients underwent hammer digit corrective surgery, Smart--Toe® provided a rigid, reproducible and stable fixation (Angirasa et al., 2012). Expanding-implants caused less invasiveness and showed no violation of the distal interphalangeal joint compared to K-wires. In another retrospective study, Smart-Toe® was compared to k-wires by considering correction of 117 hammer digits with either a Smart Toe implant or a K-wire (Scholl et al., 2013). This study reported no statistically significant differences regarding malunion, fibrous union, fracture of internal fixation, and the need for revision surgery.

3.1.3. Suture-buttons

Suture Buttons are ideal for primary or backup soft tissue to bone fixation and bone to bone stabilization. Some studies evaluated suspensory devices to fix adjacent bones at joints. In suspensory devices, suture-button anchorage provides fixation. The TightRope® system (Fig. 1C) is one of the most common fixation devices to be used in the suspension-plasty technique. The TightRope® is comprised of a FiberWire loop, tensioned and secured between metallic buttons to provide physiologic stabilization. Arthroscopic TightRope® fixation demonstrated better short-term clinical and radiological outcomes, and was associated with fewer complications compared to the traditional hook plate fixation (Bin Abd Razak, Yeo, Yeo, Lie). Moreover, it demonstrated minimal risk of ineffective fixation, or loss of function (Yao and Song, 2013). In another study, K-wires with FiberTape® resulted in a more cost-effective method, while the TightRope® system provided a shorter surgical procedure and better cosmetic outcome (Vrgočet al., 2015). Khalid and Jones reported a case of managing metacarpal arthritis employing Arthrex Mini TighRope® device (Khalid and Jones, 2012). They announced that the TightRope® device might result in over-tensioning and eventually postoperative fracture of the index metacarpal. However, a retrospective study with a minimum two-year follow-up on suture-button suspension-plasty (Mini-TightRope®; Arthrex, Naples, FL) indicated a minimum complication risk, but

Table 1
Overview of the included studies per type of fixation interaction.

Fixation method	Study type	Application	Main findings	Ref
Mechanical fixation				
Trans-osseous suture	Prospective study- 25 patients	Patellar fractures	• Safe and effective • Lower complication rate compared with the tension-band-wiring technique	Chen et al. (2013)
Bioabsorbable Cross-Pin & EndoButton	Comparative Biomechanical study-14 porcine knees of Landrace specimens	The anterior cruciate ligament (ACL) replacement	• Bio Cross-Pin technique results in stiffer fixation during cyclic loading compared with EndoButton. • Both techniques can support the immediate post-operative loading	Moré et al. (2016)
Flexible Intramedullary Absorbable Rods	Descriptive case series – 5 patients with nine shaft fractures of the fourth and/or fifth metacarpi	Fourth and fifth metacarpal shaft fractures	• Safe, simple and practical • No significant complications	Xiong et al. (2015)
Bone tissue fixation, Soft tissue fixation	Systematic review	Meniscus transplant extrusion	• Nonanatomic placement of lateral Meniscus transplants and suture fixation of medial and lateral transplants were related to greater extrusion	Noyes and Barber-Westin (2014)
Trans-osseous Suture Fixation	Review of prospectively collected data- 20 patients	Meniscal allograft transplantation (MAT)	• Preventive against meniscal extrusion after Meniscal allograft transplantation	Merkely et al. (2019)
Suture Fast-Fix (Smith & Nephew)	retrospective single-centre study, 23 patients	Meniscus allograft transplantation (MAT) is	• Repeated meniscal suturing required for two patients after two years • No proof that open surgery was superior over arthroscopy regarding the clinical outcomes	Faivre et al. (2014)
Bone tunnel fixation (bone bridge technique)	Descriptive study-new surgical technique- 30 patients	Biceps tendon pathology	• Simplicity in technique • No use of hardware • Faster soft tissue healing	Said et al. (2014)
Press-fit technique for femoral fixation, thread and additional spongiosa filling for tibial fixation	Retrospective one centre study- 69 patients	Anterior cruciate ligament (ACL) reconstruction	• Quadriceps tendon-patellar bone auto-graft performed with the press-fit tech-niqueshows in good results compared with the established procedures for primary ACL surgery using other autografts	Bariéet al. (2018)
Soft tissue (implant-free) fixation with suture	Descriptive study-new surgical technique –23 knees	Medial patellofemoral ligament (MPFL) reconstruction	• Good efficacy with reliable results • Simplicity in technique ensures reproducibility • Beneficial in cases where bone tunnels and implants need to be avoided	Kodkani and Joshi (2012)
K-Wires vs Expanding Implants	Comparative Biomechanical study-human cadaveric second toe pairs	Proximal Interphalangeal Arthrodesis of Lesser Toes	• K-wires could result in stiffer and stronger constructs in extension bending compared with the X-Fuse or Smart-Toe system	Rothermel et al. (2019)
SmartToe®	Retrospective study-28 patients	Hammer Digit Corrective Surgery	• Rigid • Reproducible • Stable	Angirasa et al. (2012)
Smart Toe® (Stryker Osteosynthesis, Mahwah, NJ)	Retrospective comparative study-86 digits included in comparison	Proximal Interphalangeal Joint Arthrodesis	• 68.8% radiographic osseous union rate • The fracture rate of 20.7% (12 of 58) • No significant difference between a Smart Toe® implant and a intramedullary K-wire regarding the complication and revision rates	Scholl et al. (2013)
TightRope® fixation vs hook plate	Comparative study- twenty-six patients with an acute ACJ dislocation	Acromioclavicular joint (ACJ) dislocation	• Arthroscopic TightRope® fixation results in better short-term clinical, radiological outcomes, and less com-plications compared to hook plate fixation	(Bin Abd Razak, Yeo, Yeo, Lie)
Suture-Button Suspensionplasty (Mini-TightRope; Arthrex, Naples, FL)	Retrospective study	Thumb Carpometacarpal Arthritis	• Minimal risk of complications • effective fixation • Minimal risk for loss of function	Yao and Song (2013)
K-wires with FiberTape® vs TightRope® fixation	Retrospective two-centre study – 16 patients	Acromioclavicular (AC) joint dislocations	• K-wires with FiberTape® results in more cost-effective outcome • TightRope® System results in shorter operative procedure, better cosmetic outcome and avoidance of intraoperative fluoroscopy	Vrgočet al. (2015)
Tightrope- Arthrex Mini TightRope (Arthrex, Naples, FL)	Case report	Advanced trapezial-metacarpal arthritis	• TightRope® device might cause over-tensioning, postoperatively fracture of index metacarpal	Khalid and Jones (2012)
Cortical suspensory fixation devices	Technical note	Posterior Cruciate Ligament Reconstruction	• Safe • Reproducible • Possibility of versatile approach	Nancoo et al. (2013)
Double button device (Tightrope: Arthrex; Naples, FL)	Retrospective study- 18 patients	Neer type IIB lateral clavicle fractures	• Intraoperative coracoid process fracture	Cho et al. (2017)

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Table 1 (*continued*)

Fixation method	Study type	Application	Main findings	Ref
Double button device (Tightrope: Arthrex; Naples, FL)	Retrospective study- 21 patients	Neer type IIB lateral clavicle fractures	• Delayed union and shoulder stiffness • Satisfactory radiologic and clinical outcomes • Implant removal is not required • Minimal risk of complications • Low implant failure • Low nonunion rates in patients with Neer type IIB fractures of the distal clavicle	Loriautet al. (2015)
Suture anchor	Controlled laboratory study- 7 matched pairs of human cadaveric ankle specimens	Repair of the lateral ankle ligaments	• No difference in the degrees to failure, torque to failure, or stiffness for the repaired ligament complex. • Nine of 14 specimens failed at the suture anchor	Gizaet al. (2013)
Juggerknot™ Soft Anchor Technique	Biomechanical *in vitro* study- 24 specimens from six cadaveric human hands	Large Mallet Finger Fractures	• Tension-band wiring was the strongest fixation method • Tension-band wiring was most prominent on the skin surface as seen in three specimens. • The JuggerKnot™ fixation had similar peak load resistance as k-wire fixation and pull-out wiring	Cheung et al. (2013)
No. zero braided permanent suture and collagen-coated FiberTape	Descriptive study-new surgical technique-78 UCL repair procedures with at least 1-year follow-up	Injuries to the medial ulnar collateral ligament (UCL)	• Stronger time-zero fixation • might have excellent long-term results.	Lall and Dugas (2017)
Bone suture anchor Mitek®	Retrospective study- 40 patients	Fractures of the medial epicondyle	• Comparable outcomes compared with the established internal fixation technique (K-wires) while Redundancy of hardware removal	Rigal et al. (2016)
Suture anchor	Retrospective study- 60 patients	Distal pole fractures of the patella	• Reduced operation time • Comparable surgical outcomes to traditional ones • Postoperative infection (11%) • Re-operation (14.8%) • Potential early hardware failure in the form of anchor pull out from the main patellar fragment	Kadar et al. (2016)
Bioabsorbable cross-pin (RIGIDfix system®: Mitek, Johnson & Johnson, USA)	Prospective study- case series, 30 patients	Transtibial posterior cruciate ligament reconstruction	• Satisfactory clinical and stability results • Risk of cyst formation	(Ahn, Lee, Choi, Chang, Lee)
Cross-pin (Mitek, Westwood, MA, USA)	Case report	Anterior cruciate ligament reconstruction	• Implant migration • The loose body presenting as a subcutaneous collection	(Boden, Razak, Hussain, McLoughlin)
Bioabsorbable cross-pins	Case report	Patella infera treatment	• Firm fixation	Jeong and Wang (2014)
Biodegradable pin PolyPIN® (Consept GmbH, Wiesbaden, Germany)	Retrospective study- 17 patients	Displaced anterior glenoid rim fractures	• Redundancy of implant removal • Minimal risk of implant-related complications • Early functional rehabilitation • Occurrence or progression of osteoarthritis	Maieret al. (2015)
Biodegradable pin and suture	*In vitro* study- porcine model	Autologous chondrocyte implantation	• Chondral suture and perpendicular pin fixation did not increase compression forces in the knee joint compared with an intact knee	Herbortet al. (2011)
Biodegradable pin (Contour™ Meniscus Arrow™; ConMed)	Animal study- Sixteen mature Merino breed female sheep	Cartilage regeneration	• Less subchondral bone alterations	Vikingssonet al. (2015)
Bioabsorbable Pins	Retrospective one centre study- 30 patients	Osteochondritis dissecans (OCD) of the knee	• Improved clinical outcomes and radiographic • High healing rates	Adachi et al. (2015)
Biodegradable pins	Retrospective one centre study- 96 patients	Osteochondritis dissecans (OCD)	• Should be chosen carefully for the lesion that presents arthroscopically stable, but as unstable status on MRI	Ishikawaet al. (2018)
Trans-osseous bioresorbable pins (Smart Nail, ConMed Linvatec, Largo, FL)	Short-term pilot study	Cartilage defects in the knee	• Frim fixation	Dhollanderet al. (2012)
Absorbable pin (stiffer poly-L-lactate absorbable pin technique)	Retrospective Case Series- 29 patients- 47 toe procedures	Hammertoe correction	• Minimal coronal angulations • No soft corns • High fusion rates • Patient satisfaction	Konkel et al. (2011)
Cellular repopulation of the ceramic building blocks including anchoring pins	Feasibility study- *in vitro* study	Tissue-engineered cartilage constructs/fixation of the grafts to the subchondral bone plate	• Stable mechanical bonding and biological milieu for the bone–cartilage interface	(Gelseet al.)
Bioabsorbable nail (LactoNail, Arthrotek, Warsaw, Indiana, USA)	Retrospective study- 7 patients		• Satisfactory outcomes • Redundancy of hardware removal	Momaya et al. (2018)

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Table 1 (*continued*)

Fixation method	Study type	Application	Main findings	Ref
		Tibial eminence fractures are in skeletally immature patients		
Absorbable chondral darts	Observational study- clinical and functional medium-term results- 25 patients	Osteochondral knee lesions of varying sizes.	• No collapse or loosening of the osteochondral graft	Kawano et al. (2012)
Tissue ingrowth				
Infiltration and In-Tissue Polymerization of Photocross-Linked Hydrogel	In vitro study	Fixation of implants to the cartilage defects	• High-strength bond between the implant and host cartilage without affecting the cell viability and tissue phenotype	Kuang et al. (2019)
Bone-ingrowth fixation (Two-dimensional ongrowth surface: plasma- spray-coated , Tridimensional ingrowth surfaces: titanium fiber, sintered cobalt-chromium and titanium beads)	Review	Bone-Ingrowth Fixation of Press-Fit Acetabular Cups	• Improving bone ingrowth with new porous materials, augmenting the biologic factors of the host bone, and reducing osteolysis.	Wiznia et al. (2019)
TiNT surfaces via an electrochemical etching process	*In vitro* experiments and *in vivo* rodent model of intramedullary fixation	Total joint replacements/ solid bone-implant fixation	• Greater bone formation • Greater Bone-implant contact • Greater strength of fixation	Bakeret al. (2020)
Laser processing with high energy density	*In vitro* study	Bond a living bone with TG ceramics using a CO2 laser	• Penetration into bone specimen interface	Ogita et al. (2012)
Laser Surface Texturing of Alumina/ Zirconia Composite Ceramics	*In vitro* study	Hip joint prosthesis	• Might be suitable for promoting bone tissue in-growth	(Baino, Montealegre, Minguella-Canela, Vitale-Brovarone)
Plasma-sprayed titanium coating	preclinical laboratory study- ovine model	Rapid and stable fixation at the bone-implant interface	• No debonding at PEEK-titanium interface • No differences regarding new bone contact on the surface of the titanium coated or time in both cortical and cancellous sites	Walsh et al. (2015)
Polyelectrolyte-multilayer coatings	*In vivo* study- 48 3-month-old male Sprague Dawley rats	Implant anchorage	• Improved implant anchorage in biomechanical testing compared with native titanium alloy	Zankovychet al. (2013)
Nanohydroxyapatite/polyamide (n-HA/ PA) prosthesis with a polyvinyl alcohol (PVA) hydrogel	*In vivo* study- 16 New Zealand white rabbits	Shoulder hemiarthroplasty	• Excellent biocompatibility and biological fixation	(Guoet al.)
Porous tantalum, titanium mesh, and beaded cobalt chromium	Comparative *in vitro* study- a tissue culture model of bone ongrowth	Implant fixation through osseointegration	• Mineralization of osteoblasts depends on implant material and surface	Ninomiya et al. (2014)
Ti6Al4V/TiC/HA composites with a reproducible porous structure	*In vitro* and *in vivo* study- 30 adult New Zealand albino rabbits	Bone–implant interface in a joint prosthesis	• Similar compressive strength to human cortical bone • No cytotoxic responses • No adverse tissue reactions • Reproducible	Choy et al. (2014)
Alendronate/hydroxyapatite (HA) coating	*In vivo* study- 15 adult mongrel dogs	Implant fixation through osseointegration	• No significant differences on bone ingrowth compared with the HA-coated control implants	Pura et al. (2016)
Modular bone morphogenetic peptide (mBMP)	*In vitro* and *in vivo* study- 12 mature female sheep	Promotes Healing of a Bone-Implant Gap	• Increased implant fixation and stimulated bone formation compared with the control	Luet al. (2012)
Recombinant human bone morphogenetic protein (rhBMP)-2 as a potent osteoinductive agent	Preclinical study- rat model	Bone repair of a critical-sized femoral defect	• Combining surgical intervention with systemic therapy might result in enhanced bone repair	a Tinsleyet al. (2015)
Intermittent injection of parathyroid hormone (iPTH)	*In vivo* study	Osseointegration	• Increased osseointegration • Increased cancellous mass • Increased the strength of the bone-implant interface	Yanget al. (2015)
Shape memory scaffold	*In vitro* and *in vivo* study- 30 adult S-D rats	Cartilage defect repair	• Simple • Less invasive • Cost-efficient	Xuanet al. (2020)
(Bio-) adhesives				
Fibrin glue	In vitro study- 8 fresh-frozen human cadaveric lower limbs	Cartilage lesions	• Stabilized the scaffold by increasing its internal layer cohesiveness and integrity in the lesions area	Filardo et al. (2014b)
Mixture of fibrin glue and autologous bone marrow concentrate (BMC)	Technical note- new surgical technique	Knee Cartilage Repair	• Safe • Effective	Gigante et al. (2012)
Nanofracturing needle and Fibrin glue	Technical note	Chondral and osteochondral defects	• Earlier rehabilitation • Encouraging early clinical results	Benthien and Behrens (2015)
Comparison of fixation principles				
Fibrin glue, cyanoacrylate, suture technique and an agarose hydrogel scaffold sealed with fibrin glue	Comparative Biomechanical study- human cadaveric model- six hips for each fixation methods	Focal chondral injuries	• Fibrin glue does not provide sufficient fixation • Cyanoacrylate not stable enough • The suture and hydrogel scaffold technique were the most reliable	Cassar-Gheiti et al. (2015)
				Baueret al. (2012)

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Table 1 (*continued*)

Fixation method	Study type	Application	Main findings	Ref
Fibrin glue, Suture, Bioabsorbable smart nails	Case series with prospective clinical and MRI follow-up over 5 years-18 patients	Younger patients with medial knee osteoarthritis (OA)	• Fibrin glue and sutures turned to be insufficient • Caused graft detachments	

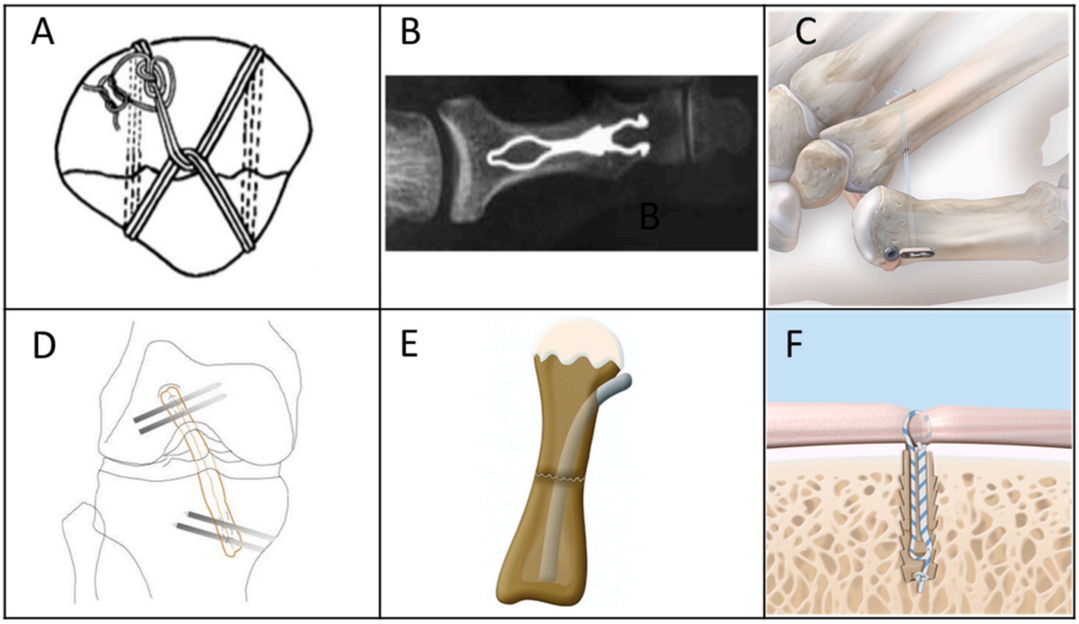

Fig. 1. A. Trans-osseous sutures (Chen et al., 2013) B. Smart-Toe® system (Khan, Kimura, Ahmad, D'Souza, D'Souza) C. TightRope® system (Photo courtesy of Arthrex) D. RigidFix® pins (Stengelet al.) E. Absorbable rod (Xiong et al., 2015) F. Soft anchor, Knotless SutureTak® (Photo courtesy of Arthrex).

ineffective fixation, and loss of function (Yao and Song, 2013). According to a technical note, the cortical suspensory fixation device has been used for posterior cruciate ligament reconstruction, which provided safe and reproducible results (Nancoo et al., 2013). In addition, efficacy of the suture-button technique for stabilization have been reported for treating clavicle fractures (Cho et al., 2017) (Loriautet al., 2015).

One of the contributing factors involved in meniscal extrusion after Meniscal Allograft Transplantation (MAT) appeared to be inadequate fixation. For this purpose, Faivre *et al* evaluated the FAST-FIX™ (Smith & Nephew) (Faivre et al., 2014) meniscal repair system. In arthroscopic MAT, the FAST-FIX system which consists of suture wires attached to tags been inserted through bone tunnels to fix the graft to the residual meniscus wall and to the capsule. They reported no significant differences between arthroscopic MAT and open surgery where the graft is fixed with sutures to the capsule and the displaced popliteus/lateral collateral ligament complex is re-attached by the screw-washer system.

3.1.4. *Suture-anchors*

Suture anchors are tiny implants that are usually used to fix soft tissue to bone through a variety of innovative anchor styles, materials and suture configurations. Bio-SutureTak (Fig. 2A) anchors (Arthrex Inc, Naples, Florida) have been utilized in both open and arthroscopic repair of the lateral ligament ankle complex (Gizaet al., 2013). These biodegradable anchors are press-fit anchors containing a built-in-suture to augment the strength of the anchor. They reported no differences regarding number of failed suture-anchors, torque to failure, or stiffness between open and arthroscopic surgery outcome, while 9 (4 open and 5 arthroscopic) out of 14 suture anchors failed at the suture-anchor or ligament-suture interface. Another study assessed the peak load resistance of the Juggerknot™ soft anchor technique compared to traditional fixation methods to treat large mallet finger fractures (Cheung et al., 2013). This showed that Juggerknot™'s peak load resistance is comparable to that of K-wire fixation and pull-out wiring (twisting the two ends of a stainless-steel wire which has been passed through the inserted hole on top of the bone opening). In another study, a combination of a

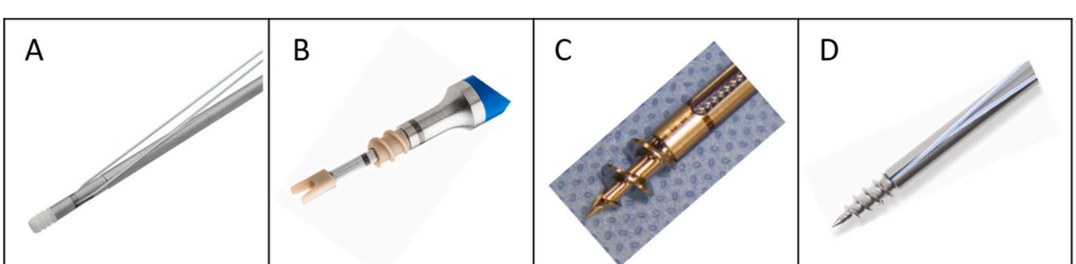

Fig. 2. Suture-anchors; A. Bio-SutureTak® (Photo courtesy of Arthrex), B. 3.5 mm DX SwiveLock® (Photo courtesy of Arthrex), C. 5 mm Fastin RC (Zhanget al., 2012), D. 3.5 mm Corkscrew® FT (Photo courtesy of Arthrex).

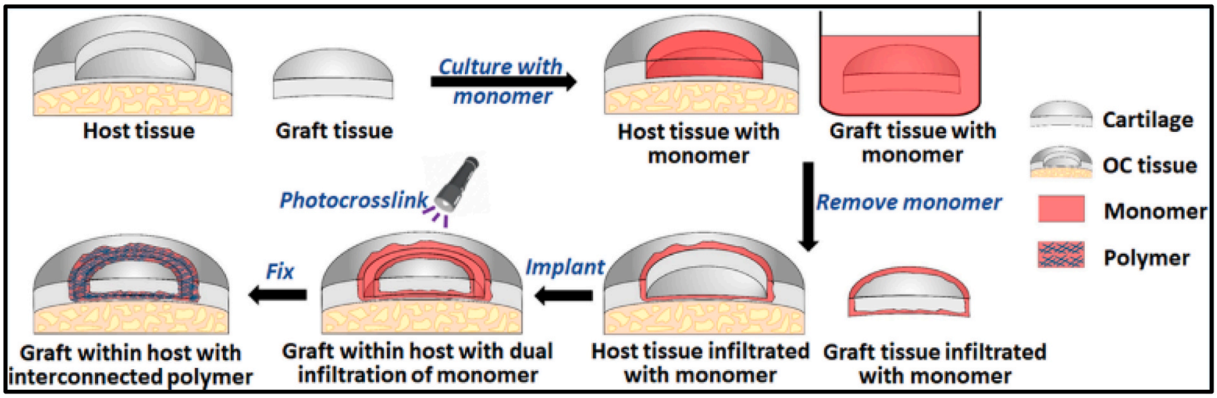

Fig. 3. Schematic diagram of a new fixation technology. In this approach, the implant (cartilage) and host osteochondral (OC) tissue were pre-infiltrated with the DLLA-EG/LAP solution. Afterward, the implant was placed into the defect area of the host tissue, and an additional DLLA- EG/LAP solution was applied to fill the void space in between. The entire construct was then subject to illumination. Finally, an interconnected and continuous polymer network was formed, which created a strong fixation between the host and graft tissue (Kuang et al., 2019).

SwiveLock® anchor (Fig. 2B) and a Corkscrew® anchor (Fig. 2D) has been used to repair ulnar collateral ligaments (Lall and Dugas, 2017). The SwiveLock includes fully-threaded Twist-In knotless anchors designed for use with suture, and soft tissue grafts in repair and reconstruction techniques. Tension is visualized, adjusted and the suture is locked into position with the SwiveLock anchor body. The anchors are available in bioabsorbable BioComposite or PLLA and nonabsorbable PEEK or titanium materials. The Nano, Micro, Mini and 3.5 mm Corkscrew® suture anchors are designed with a fully threaded length to create cortical anchorage in smaller bones. In a retrospective study including 40 patients, utilizing bone suture anchors (Mitek® non-resorbable bone suture anchor) for fractures of the medial epicondyle in children has been evaluated (Rigal et al., 2016). This study showed no significant difference regarding flexion-extension of the elbow and rate of hypertrophy of the medial epicondyle compared to using k-wires as the conventional fixation technique. However, utilizing bone suture anchors is associated with eliminating the need for removal of hardware which results in less morbidity and cost. Suture anchors (Fastin (Fig. 2C) and Panalok, Depuy, Warsaw, IN) resulted in comparable results while reducing the time of operation comparing to the traditional techniques for treating distal pole fractures of the patella (Kadar et al., 2016). However, infection, re-operation and potential early hardware failure in the form of anchor pull out from the main patellar fragment been reported as their drawbacks.

3.1.5. *Pins*

We retrieved interesting articles reporting long-term clinical evaluations of pins as fixation technique. Pins are mainly used for soft tissue to bone fixation, for synthetic scaffolds and allografts-to-bone fixation, and bone-to-bone fixation. The anchorage strength of bioabsorbable cross-pins for ligament fixation has been compared to using endobuttons for this application (Moré et al., 2016). It turned out that the absorbable pins can form a stiffer fixation and are able to support immediate post-operative forces. However, using a bioabsorbable cross-pin (RIGIDfix system®: Mitek, Johnson & Johnson, USA) could result in cyst formation regardless of satisfactory clinical and stability results (Ahn, Lee, Choi, Chang, Lee). In addition, pin migration and loosening have been reported when the Cross-pin system (Mitek, Westwood MA, USA) was employed (Boden, Razak, Hussain, McLoughlin). In application of treating patella infera, bioabsorbable Cross-pins resulted in firm fixation (Jeong and Wang, 2014). Bioabsorbable pins turned out to be a feasible and safe method to treat anterior glenoid rim fractures up to a glenoid defect size of about 35%. The study reported no need for implant removal, minimal risk of implant-related complications and early functional rehabilitation as advantage of the technique, but occurrence or progression of osteoarthritis as drawback (Maieret al., 2015). In an in-vitro study, Herbort et al. investigated the importance of fixation pins on joint compression forces after arthroscopic fixation of matrix-associated autologous chondrocyte implantation at the knee joint in a porcine model. They reported no increased compression force after chondral suture and perpendicular pin fixation compared to an intact knee (Herbortet al., 2011). Anchoring a biodegradable polycaprolactone (PCL) scaffold with a poly(L-lactic acid) (PLLA) pin has been compared to press-fitting the scaffold to the defect after microfracturing for articular cartilage regeneration (Vikingssonet al., 2015). This study reported fewer subchondral bone alterations, usually recognized after microfracture surgery, when fixing the scaffold by a pin. Utilizing bioabsorbable pins for Osteochondritis dissecans (OCD) of the knee has been described in two retrospective studies. While one study indicated improved clinical result and high healing rate (Adachi et al., 2015), the other study announced the limitation of in-situ arthroscopic fixation (Ishikawaet al., 2018). These evaluations revealed that the true lesion stability and the lesion size could be a critical factor that can limit the efficacy of arthroscopic in-situ fixation. Trans-osseous bioabsorbable pins (Smart Nail, ConMed Linvatec, Largo, FL) created firm fixation of implants into cartilage defects of the knee in a short-term pilot study (Dhollanderet al., 2012). In another retrospective study, absorbable pins have been employed for 29 patients with 47 hammertoe correction procedures (Konkel et al., 2011). The pin fixation resulted in minimal chondral angulation and a high fusion rate. Bauer et al. compared the performance of fibrin glue, suture and bioabsorbable smart nails (Baueret al., 2012). They reported that use of bioabsorbable pins resulted in satisfactory outcomes, while only applying sutures and fibrin glue turned out to be insufficient and caused graft detachments. In a feasibility study, a lattice construct of anchoring pins was fixed to the subchondral bone while its ceramic building blocks were filled with cell-loaded hydrogels. This technique provides the mechanical anchoring while preparing a biological environment for the bone-cartilage interface. The novelty of this bio-mechanical approach is that pins as fixation module are not disruptive elements but represent an integral part of the lattice structure, which results in biological joint resurfacing (Gelseet al.). In another application, arthroscopic fixation of tibial eminence fractures with bioabsorbable nails (LactoNail, Arthrotek, Warsaw, Indiana, USA) resulted in satisfactory outcomes, associated with the redundancy of a second operation for hardware removal (Momaya et al., 2018). Using absorbable chondral darts has been reported for fixation of grafts in patients suffering from osteochondral knee lesions of varying sizes (Kawano et al., 2012). This study announced good clinical results and low morbidity at the donor site in the medium term.

3.1.6. Rods

One article reported on the use of a flexible intramedullary absorbable rod (Fig. 1E) for a bone-to-bone fixation. A self-reinforced poly-L-lactide (SR-PLLA) absorbable rod (Biofix, Conmed Linvatec Biomaterial Ltd., Finland) with a diameter of 2 mm was used to manage fourth and fifth metacarpal shaft fractures (Xiong et al., 2015). Nine shafts were operated, resulting in a good clinical outcome without clinical complications.

3.2. Tissue-ingrowth techniques

Tissue ingrowth methods have been reported to fix an implant to bone or cartilage by osseointegration or chondrointegration at the tissue-implant interface. The majority of the studies, which explored implant anchorage through osseointegration, reported *in vitro* and *in vivo* experiments, including preclinical animal studies.

3.2.1. Osseointegration

To achieve long-term osseointegration, the implant must gain initial rigid stability with limited micromotion (Wiznia et al., 2019). The methods which have been utilized to form direct implant-bone fixation are based on either surface modifications and coatings, or osseoinductive agents.

3.2.1.1. Surface modifications. The surface modifications and coatings include electrochemical etching (Bakeret al., 2020), pulsed laser radiation (Ogita et al., 2012) (Baino, Montealegre, Minguella-Canela, Vitale-Brovarone), plasma-sprayed titanium coating (Walsh et al., 2015), polyelectrolyte multilayer coating (Zankovychet al., 2013), and coating with polyvinyl alcohol (PVA) hydrogel (Guoet al.). With the surface modifications an environment is achieved which enhances cell adhesion, proliferation, migration and calcification. Moreover, the prepared environment can potentially facilitate mechanical interlocking via ingrowth of tissue (Wiznia et al., 2019).

One approach is to modify the implant surface topography. The implant surface must promote ingrowth and maintain contact with viable bone (Wiznia et al., 2019). It has been hypothesized that the produced roughness would promote bone formation. Baker et al. compared unmodified titanium alloy surfaces with electrochemically by conducting in-vitro and in-vivo studies (Bakeret al., 2020). The titania nanotube (TiNT) electrochemically etched from the titanium alloy (Ti–6Al–4V ELI) with two different morphologies: traditional vertically oriented and aligned TiNT morphology (Aligned TiNT), and a newly developed variant with an interconnected, trabecular bone-like morphology (Trabecular TiNT). They reported increased bone formation and stronger implant fixation in femora for TiNT-etched surfaces. The average fixation strength of the Trabecular TiNT and Aligned TiNT groups reported 1.87 and 2.29 MPa respectively at a 12-week endpoint. One critical factor in implant fixation is early proliferation of cells into the porous ingrowth surface, followed by delayed maturation of osteoblasts and formation of new bone (Ninomiya et al., 2014). Pulsed laser radiation has been used to add texture to flat sintered alumina/zirconia composite ceramics on hip prostheses (Baino, Montealegre, Minguella-Canela, Vitale-Brovarone). In another study, laser radiation has been utilized to form a porous foam-like substance to anchor a bovine cortical bone specimen to a ceramic composed of TCP and MgO–Al2O3–SiO2-glass (TG ceramics) (Ogita et al., 2012). This study outlined a direct relationship between the strength of fixation and duration of laser irradiation.

Another approach to realize a surface modification is by adding additional material to the surface of an implant. Applying hydroxyapatite (HA) onto titanium alloy implants via a rapid microwave sintering technique resulted in titanium alloy/HA composites with a reproducible porous structure as a suitable bone-implant interface for bone formation (Choy et al., 2014). Even though mechanical and physical properties of polyetheretherketone (PEEK) reveal advantages for implant devices, the hydrophobic nature and the lack of direct bone contact remains a limitation. Plasma-sprayed titanium coating on PEEK implants can improve shear strength at the bone-implant interface (Walsh et al., 2015). In an animal study, functionalizing the surface of titanium alloy implants by depositing natural polyelectrolyte multilayers of chitosan/hyaluronic acid and chitosan/gelatin coatings revealed positive effects on bone-implant anchorage (Zankovychet al., 2013).

3.2.1.2. Osseoinductive agents. To improve the fixation of porous implants, osseoinductive agents like growth factors, osseoinductive proteins, or other bone formation regulators can be delivered as adjunct therapy. Studies reported release of biphosphate alendronate (Pura et al., 2016), release of modular bone morphogenetic peptide (mBMP) (Luet al., 2012), local release of recombinant human bone morphogenetic protein (rhBMP)-2 combined with systemic administration of Scl-Ab (a Tinsleyet al., 2015) and injection of the parathyroid hormone (iPTH) (Yanget al., 2015).

3.2.2. Chondrointegration

Chondrointegration is applied to achieve biological fixation of cartilage scaffolds and grafts. Traditional fixation methods for cartilage scaffolds are press-fitting, suturing, subchondral pinning and using fibrin glue. Sutures and subchondral pins can cause damage to cartilage, while fibrin glue turned to be weak and rapidly degradable. In an *in-vitro* study, photo-cross-linked hydrogel has been used to fix a cartilage implant into the host tissue (Kuang et al., 2019). In this new fixation technology, the visible-light photoinitiator lithium phenyl-2,4, 6-trimethylbenzoylphosphinate (LAP) has been used to photo-cross-link a chondro-supportive scaffold, Poly- D,L-lactic acid/-polyethyleneglycol/poly-D,L-lactic acid (PDLLA-PEG). An interconnected and continuous hydrogel structure is formed, which fixes the implant within the host cartilage after the infiltration of LAP and DLLA-PEG into the implant and host cartilage (Fig. 3). A strong bond between the implant and cartilage have been formed without morbidity or change of host tissue.

In another study, employing a shape memory scaffold to treat cartilage defects has been reported as less-invasive, biocompatible and cost-efficient approach (Xuanet al., 2020). In this technique, a chondrogenic shape-memory ternary scaffold was implanted via a minimal-invasive procedure (Fig. 4). The scaffold contained poly (glycerol sebacate) (PGS), crystallized poly (1,3- propylene sebacate) (PPS) and immobilized bioactive kartogenin (KGN). A poly (glycerol sebacate) (PGS) covalent network determines the compact permanent state. After implantation, crystallized poly (1,3-propylene sebacate) (PPS) provides a reversible switch phase at approximately body temperature to fix the temporary state and fill the defect. According to their evaluations, seeded bone marrow mesenchymal stem cells (BMSCs) on the PPS/PGS/KGN scaffolds showed high expression levels of aggrecan which has the ability to bind to hyaluronan and chondrocytes to form crosslinked network bonds between the implant and the host tissue.

3.3. (Bio-)adhesives

Adhesives form an anchorage based on a chemical and/or physical bonding rather than relying on bulky mechanical interlockings. In contrast to tissue-ingrowth methods which are long-term fixations, adhesives can be considered as both short- and long-term fixation techniques. Adhesives should meet specific requirements in terms of biocompatibility, biodegradability and strength depending on their applications. Among a wide range of adhesives tested and utilized for medical applications, only fibrin glue has been reported in the reviewed articles to be used in clinical applications of joint disorders. It has been widely employed in fixing scaffolds and grafts to manage articular cartilage injuries. Biomechanical cadaveric studies indicated improved

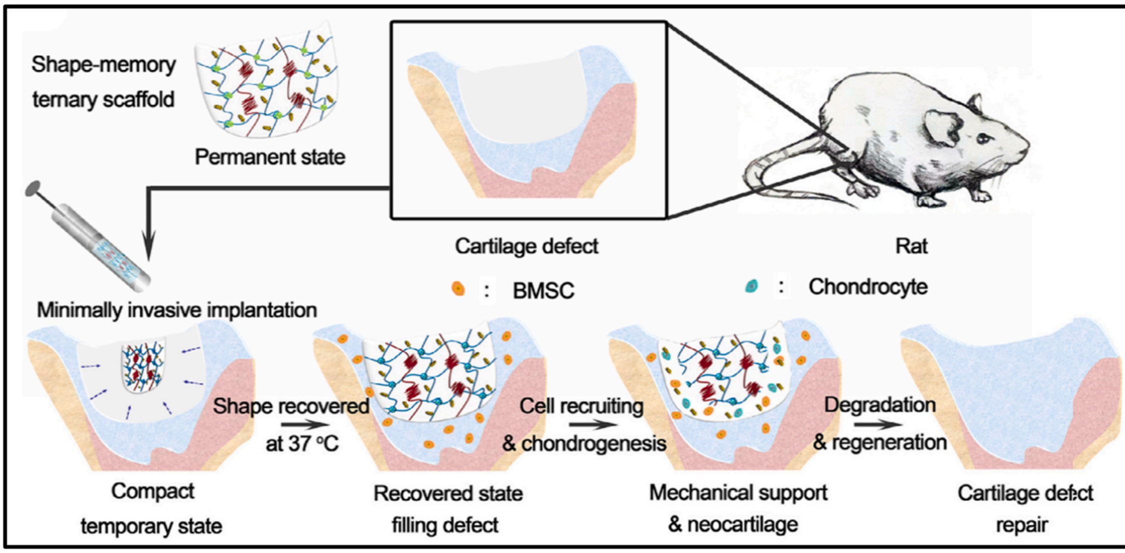

Fig. 4. Minimally invasive implantation of the scaffolds and subsequent cartilage regeneration processes, including cell recruiting and chondrogenesis, mechanical support, neocartilage, scaffold degradation and regeneration, and cartilage defect repair, in a rat knee model (Xuanet al., 2020).

scaffold integrity and stability by using fibrin glue prior to press-fitting the scaffolds compared to the press-fit technique without fibrin glue. (Filardo et al., 2014b). However, the fixation is weak and the rate of degradation is high (Kuang et al., 2019). In an *in vitro* comparative study, both commercial fibrin glue (Tisseel™) and N-butyl-2-cyanoacrylate (Glubran® 2) have been used for fixation of chondral flaps in a series of human cadaveric hip joints. Both adhesive systems failed after a specific number of cycles and showed inferior performance compared to sutures and hydrogel scaffolds.

Few studies reported the combined use of fibrin glue as temporary fixation of cartilage scaffolds with modified microfracturing or nano-fracturing as long-term biological regeneration technique (Gigante et al., 2012) (Benthien and Behrens, 2015). These studies did not report any complications regarding insufficient fixation of grafts. They reported employing 10:1 mixture of fibrin glue and bone marrow concentrate (BMC) to fix a collagen membrane into a cartilage defect and also cover it with the mixture at a knee joint (Gigante et al., 2012). This study combined BMC which has been indicated to promote cartilage regeneration with covered microfracture technique to address full-thickness, focal, condylar cartilage defects. The study did not report detachment of the graft, but harvesting marrow blood percutaneously can cause morbidity on the iliac crest.

4. Discussion

An adequate anchoring system must meet specific requirements, like strength, biocompatibility, life-time and sterilizability. Several new systems have been developed and tested, which show promising results as delineated in this review. The fixation techniques can be categorized based on the main interaction that leads to attachment and anchorage.

Mechanical fixations provide the strongest anchorage. They are highly stiff and show reproducible results, which make them a good candidate in high-loading situations. Among the diverse mechanical fixations, sutures and biodegradable pins are the main anchoring forms to be used. The more recent and novel fixation devices such as suture-button and soft anchor techniques might be considered as a hybrid design of suture- and pin-like interlockings. This highlights the evolution of mechanical fixations from general anchorage tools like K-wires toward application-specific designs. Moreover, biodegradable materials play an important role in the modern fixation techniques.

Several studies confirmed the effectiveness of surface treatments and manipulation of osteoinductive agents to promote **tissue-ingrowth fixation**. The approach for encouraging bone formation at the implant-bone interface was either by introducing bioactive elements or fabricating a porous surface suitable for osteoblast proliferation. Even though osteoinductive implants are commercially available and turned into the common practice, new techniques been developed to form the tissue-implant anchorage. These new techniques address new materials, add nanoscale topographical features promoting cell attachment or overcome previous technique's drawbacks. All of the reviewed studies that reported novel tissue-ingrowth fixation techniques were at pre-clinical stage. This outlines the need of future research in this field to assess these novel bone-ingrowth techniques during clinical trials. A chondroinductive implant that also serves as fixation system could bring numerous advantages in applications for treating articular cartilage injuries. Another novel technique for this application is infiltration of a polymer or scaffold incorporated with functional small molecules which could promote chondrogenesis.

From a theoretical point of view, **(bio-)adhesives** as minimal-invasive fixation systems appear to be highly interesting. However, the reviewed article reported solely fibrin glue as an option in clinical applications, because the majority of adhesives developed in the field of orthopedics are reported as bone-to-bone adhesives for fractures and are not considered as a potential fixation system for joint implants. Investigating the potential application of these formulations for implant fixation may prove to be an interesting approach to expand the use of adhesives for this purpose. Two comprehensive review articles on bone adhesives have been recently published; one evaluating chemistry and adhesion mechanism of bone adhesives (Sánchez-fernández et al., 2019), and the other one evaluating what still is required to make them applicable in practice (Bökeret al., 2019). The only application of fibrin glue that was reported included the fixation of grafts for chondral lesions. Fibrin glue demonstrated inferior results in terms of stability and integration compared to other fixation options. Hybrid techniques using fibrin glue and micro- or nano-fracturing or a mixture of fibrin glue and autologous BMC have been assessed and showed better outcomes.

5. Conclusion

Fixation systems might perform an important role in both implant-based and implant-less surgical procedures to maintain integrity of soft-to-soft tissue or soft-to-bone tissue connections at joints. This review paper demonstrates the range of novel fixation systems for treating disorders at joints, either at first-stage of *in vitro* assessments, or at final clinical applications. This is insightful for designers and surgeons not only to optimize current surgical techniques, but also to serve as inspiration for future novel implantation techniques. In most cases (further long-term) clinical studies are required to evaluate these novel fixation techniques and to explore their (alternative) clinical applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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