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Review

Remaining Hurdles for Tissue-Engineering the Temporomandibular Joint Disc

Ryan P. Donahue,¹ Jerry C. Hu,¹ and Kyriacos A. Athanasiou^{1,*}

The temporomandibular joint (TMJ) disc, a fibrocartilaginous structure between the mandible and temporal bone, is implicated in temporomandibular disorders (TMDs). TMDs symptomatically affect approximately 25% of the population; of which, 70% have internal derangement of the disc. Treatments lack efficiency, motivating novel therapies, including tissue-engineering toward TMJ disc regeneration. Recent developments in scaffold-based or scaffold-free approaches, cell sources, and biochemical and mechanical stimulation have resulted in constructs exhibiting native tissue mechanics. Safety and efficacy of tissue-engineered implants have shown promising results in orthotopic animal studies. However, many hurdles need to be overcome in tissue-engineering approaches, and clinical and regulatory pathways. Future studies present an opportunity for clinicians and researchers to work together toward safe and effective clinical trials.

Motivation for Tissue-Engineering of the TMJ Disc

The temporomandibular joint (TMJ) is a **ginglymoarthrodial joint** (see [Glossary](#)), central to speaking and chewing functions [1]. The TMJ contains a disc between a condyle and the glenoid fossa-articular eminence region [2] ([Figure 1](#)). The TMJ disc is biconcave and fibrocartilaginous in nature [2]. As the TMJ articulates, the TMJ disc may distribute the stresses that develop within the joint [3] ([Figure 1](#)). Trauma [4] and age-related degeneration [5] can cause abnormal loading in the TMJ, leading to temporomandibular disorders (TMDs). TMDs are characterized by orofacial pain and/or limitation in jaw movement [6–8], and symptoms are present in approximately 25% of the population [9]. Perplexingly, TMDs affect women up to eightfold more than men [9–12]. In addition, TMDs affect mostly younger patients between 20 and 50 years of age [12–14]. As the second most common musculoskeletal condition resulting in pain and disability, TMDs cost an estimated \$4 billion per annum in the US (<https://www.nidcr.nih.gov/research/data-statistics/facial-pain>).

A specific subset of TMDs involves discal pathologies such as **internal derangement (ID)**, disc thinning, and disc perforation. ID affects about 70% of TMD patients [15]. Severe cases of ID present with disc thinning and eventual disc perforation ([Figure 2](#)) in 5–15% of ID patients [5, 16, 17]. However, ID and disc perforation can occur independently; the independent cases of disc perforation can be due to age-related wear [5]. These discal pathologies are the most prevalent manifestation of TMDs [15]. **Osteoarthritis (OA)** is also commonly seen in conjunction with ID [16, 18], but the relationship between ID and OA is not understood; it is not known whether one precedes the other or if both share common causative events [18]. However, it is thought that TMJ disc pathologies such as ID or disc perforation are the first steps in a series of degenerative changes (i.e., OA) seen throughout the adjacent articulating, soft tissue surfaces [19].

Management of disc-related TMDs varies with disease severity [20]. Non- and minimally invasive strategies include physical therapy [21], occlusal splints or adjustments [22],

Highlights

Current treatments for TMDs lack long-term efficacy and are palliative, motivating tissue-engineering for repair or replacement of the injured or ailing tissues in the TMJ, such as the disc.

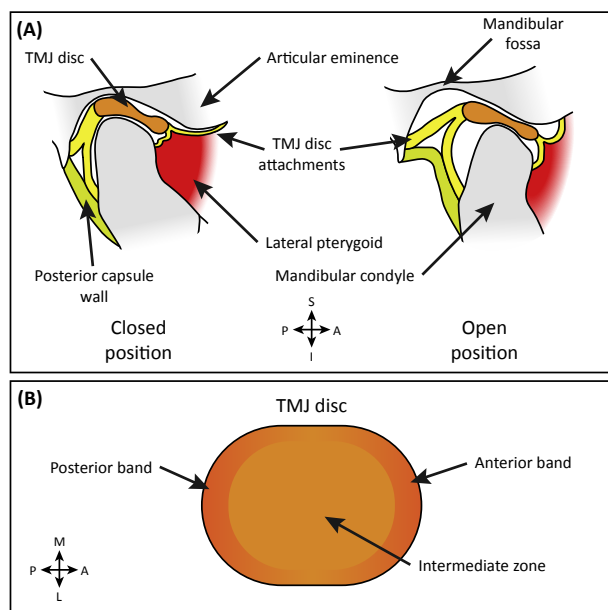
Scaffold-based or scaffold-free approaches, cell sources, biochemical stimuli, and mechanical stimuli are all elements of the tissue-engineering process that need to be considered to tailor TMJ disc construct properties.

Large animals can serve as models of human TMDs orthotopic implantation in large animal models is a necessary translational step.

The first successful orthotopic study of the TMJ disc in a large animal model has primed the field for translation of tissue-engineered constructs; however, there are still numerous hurdles prior to human clinical trials.

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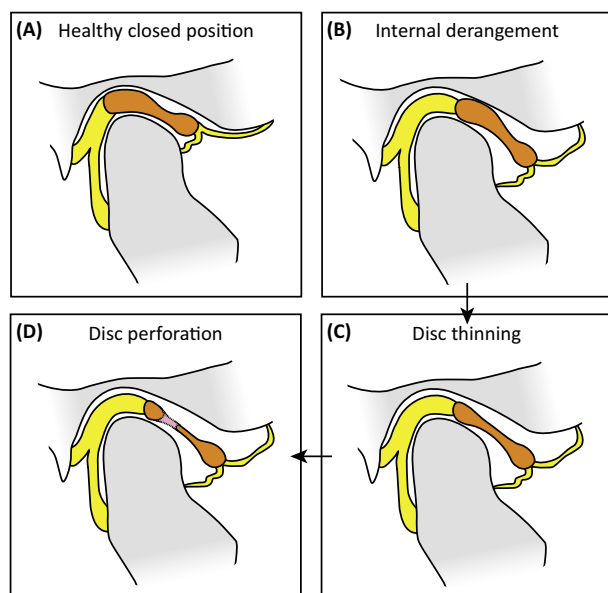
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Figure 1. TMJ Disc Anatomy. (A) Depending on the open or closed position of the joint, the TMJ disc is situated between the mandibular condyle and the articular eminence-mandibular fossa region. In this sagittal view, the disc is held in place by disc attachments, present at all angles (e.g., lateral, medial, posterior, anterior), surrounding the disc. The joint is separated into two joint capsules delineated by the TMJ disc. (B) The disc is regionally composed of two bands in the anterior and posterior portions of the disc. The middle portion of the disc is referred to as the intermediate zone. Abbreviations: A, anterior; I, inferior; L, lateral; M, medial; P, posterior; S, superior; TMJ, temporomandibular joint.

pharmacologic agents [23], sodium hyaluronate and corticosteroid injections [24], arthrocentesis [25], and arthroscopy [16]. However, these treatments are only palliative. Only 5% of TMDs are candidates for surgical intervention [26]; surgeries for TMDs include discectomy with or without disc replacement [27] and partial or full joint reconstruction with autologous [28] or



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Figure 2. Internal Derangement of the TMJ Disc. (A) A healthy closed jaw position is shown. (B) The most common type of internal derangement is shown, where the disc is displaced anteriorly. Progression of the joint in this configuration often causes (C) disc thinning and (D) eventual disc perforation.

Glossary

Ginglymoarthrodial joint: joint functioning in both rotation and translation.

Internal derangement (ID): misalignment or displacement of the TMJ disc from a normal anatomical position.

Mastication: mechanical grinding of food into smaller pieces by teeth.

Osteoarthritis (OA): slowly progressing joint disease characterized by degenerative changes in the cartilage and subchondral bone; presents through wear of the cartilage or underlying bone and presence of osteophytes; commonly affects large diarthrodial joints such as the knee, but also joints such as the TMJ.

OA score: semiquantitative measure of severity of OA based on histomorphological analysis of cartilage, underlying bone, and degenerative marks such as osteophytes; a higher number indicates increased degeneration; standardized by various groups including the Osteoarthritis Research Society International (OARS) and the International Cartilage Regeneration and Joint Preservation Society (ICRS).

Ruminants: even-toed, hoofed mammals (e.g., bovine, ovine) that chew regurgitated food from their first stomach.

Young's modulus: material property defining the stiffness of a material when deformed by uniaxial tension or compression; measured as the ratio of stress (force per unit area) to strain (change in length divided by original length).

alloplastic materials [29]. Discectomy has shown promise for symptom reduction but has shown degenerative remodeling of the joint as a result [30,31]. Costochondral rib grafts are used to reconstruct the mandibular condyle [28], but no autologous grafts exist for the complete joint [14]. Alloplastic total joint prostheses have been indicated for severe ankylosis, failure of autologous grafts, failure of Proplast-Teflon implants, or severe OA [32]. Most TMD patients range between 20 and 50 years of age [12–14], but the typical lifetime of alloplastic total joint prostheses is 10–15 years [33], making revisions likely within a patient's lifetime [14]. The use of alloplastic total joint prostheses is reserved as an option of last resort for a small subset of patients, creating a gap in terms of treatment options between non- or minimally invasive strategies and end-stage surgical techniques.

The treatments described above do not provide mid-stage intervention for patients. To fill this gap, novel treatment strategies to improve patient outcomes must be developed. Tissue-engineering aims to regenerate the pathological tissues in TMD with biological neotissues to restore long-term function. Here, we focus on TMJ disc pathologies due to their overarching prevalence in TMDs [15]. In particular, we discuss recent tissue-engineering efforts (Table 1) and remaining hurdles for TMJ disc tissue-engineering.

Recent Tissue-Engineering Efforts

Tissue-engineering uses scaffolds, cells, and various signals such as biochemical and mechanical stimuli (Figure 3). As discussed in this section, advances in materials engineering have resulted in a variety of scaffolds [34–36], while scaffold-free approaches, such as the self-assembling process [37–39], have also emerged in TMJ disc tissue-engineering. In terms of cell sources, primary chondrocytes, mesenchymal stem cells (MSCs), and cell expansion technologies are also reviewed below (Table 1). Signals such as biochemical and mechanical stimuli for mechanical improvement of the TMJ disc (Table 1) are also discussed. This section also examines small animal models that have been used for examining the performance of these implants [36,39–43].

Novel Scaffold-Based and Scaffold-Free Approaches

The primary purpose of scaffolds is to provide a template for cells to form tissues. Scaffolds can be functionalized with biomolecules to direct cell behavior and manufactured with mechanical properties similar to the tissues they are intended to replace. Ideally, scaffold degradation rates match the rate of tissue formation. Scaffolds recently used in tissue-engineering the TMJ disc include natural materials and synthetic materials (Table 1). Two particularly interesting developments include novel scaffold fabrication methods and the emergence of scaffold-free approaches.

New fabrication methods allow for surface modifications of scaffolding materials. Layer-by-layer nanoassembly is one such fabrication method [34,44]. Titanium dioxide nanofilms are used to modify surfaces of scaffolds for tissue-engineering of bone [44] as well as cartilage [34]. These nanofilms are created by layer-by-layer nanoassembly, based on the principle of electrostatic charge, to coat various surfaces allowing for increased cell attachment, control of cell phenotype, and control of differentiation. In a study using titanium dioxide surface modification with seeded TMJ disc cells, cell proliferation and extracellular matrix (ECM) deposition increased with increasing thickness of nanofilms [34]. The matrix was reminiscent of a fibrous ECM, in contrast to a cartilaginous ECM. Type I collagen and decorin, approximately 0.34 and 0.31 mg/mL, were present in higher amounts than type II collagen and aggrecan, approximately 0.14 and 0.28 mg/mL, after 14 days of culture on 20 layers of titanium dioxide nanofilms [34]. Additional work needs to be performed to couple layer-by-layer

Table 1. Recent Tissue-Engineering Studies of the TMJ Disc Published Since 2013

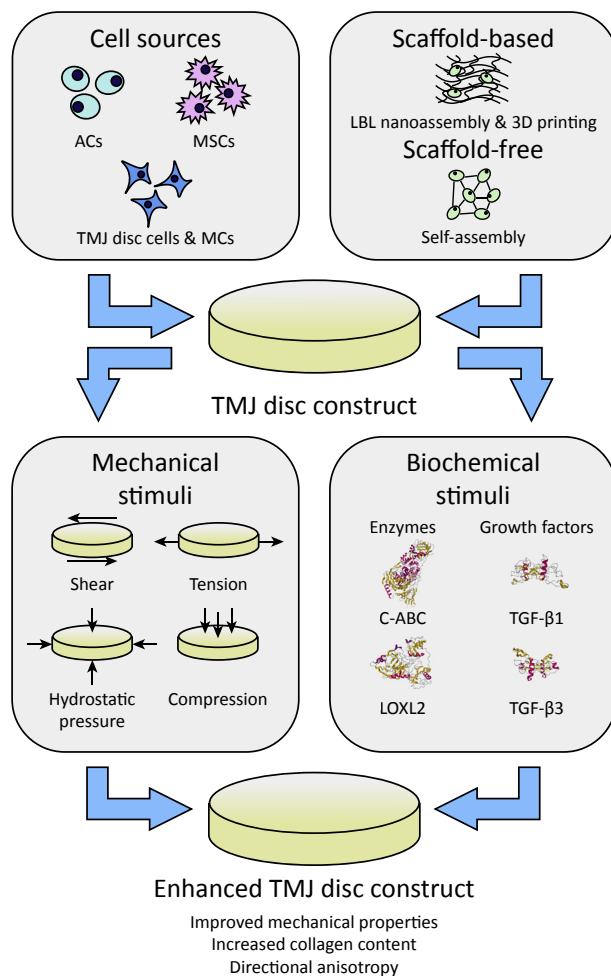
Authors (year)	Refs	Scaffold-based or scaffold-free approach	Cell sources	Species of cell sources	Biochemical stimuli	Mechanical stimuli	Animal model tested (implantation site)
Vapniarsky <i>et al.</i> (2018)	[39]	Self-assembling process	CCs expanded to passage 3	Yucatan minipig	TGF- β 1, C-ABC, LOXL2	Passive axial compression	Yucatan minipig (orthotopic)
Matsuka <i>et al.</i> (2018)	[57]	Decellularized TMJ discs	Wharton's jelly-derived MSCs	Human	None	None	None
Bousnaki <i>et al.</i> (2018)	[55]	Chitosan and alginate scaffolds	Dental pulp stem cells and nucleus pulposus cells	Human	Unidentified ^a	None	None
Wang <i>et al.</i> (2018)	[51]	Coculture cell sheet seeded on PLGA electrospun scaffolds	TMJ disc cells and synovium-derived MSCs	Rabbit	TGF- β 3	None	None
Ronald & Mills (2016)	[34]	Titanium dioxide nanofilms	TMJ disc cells	Cow	None	None	None
Tarafder <i>et al.</i> (2016)	[36]	PCL scaffolding with PLGA microspheres	Bone marrow-derived and synovium derived MSCs	Human/rabbit	CTGF, TGF- β 3	None	Rabbit (orthotopic)
Legemate <i>et al.</i> (2016)	[35]	PCL scaffolding with PLGA microspheres	Bone marrow-derived MSCs	Human	CTGF, TGF- β 3	None	None
Juran <i>et al.</i> (2015)	[56]	Decellularized TMJ discs with laser micropatterning	Wharton's jelly-derived MSCs	Pig	Epidermal growth factor, platelet-derived growth factor BB	None	None
Wu <i>et al.</i> (2014)	[40]	Fibrin gel and chitosan scaffold	Synovium derived-MSCs	Rat	TGF- β 3	None	Nude mice (subcutaneous)
MacBarb <i>et al.</i> (2013)	[38]	Self-assembling process	ACs and MCs	Cow	TGF- β 1, C-ABC	Passive axial compression	None
Ahtiainen <i>et al.</i> (2013)	[41]	PLA scaffold	Subcutaneous adipose-derived MSCs	Rabbit	TGF- β 1	None	Rabbit (orthotopic)

Summary of the scaffold-based or scaffold-free approaches, cell sources, species, biochemical stimuli, mechanical stimuli, and implantation sites of the constructs are provided.

^aIt is unclear which biochemical stimuli are in the chondrogenic medium used in the study by Bousnaki, *et al.* because it was a proprietary formulation.

nanoassembly with typical scaffold materials such as polycaprolactone (PCL) or polylactic acid (PLA).

3D printing is a fabrication technique that achieves microprecise placement of scaffolding materials and functional biomolecules. 3D printing can create regional variation in scaffolds reminiscent of the native TMJ disc. For example, a dual-nozzle setup in a PCL-poly(lactic-co-glycolic acid) (PLGA) microsphere system allowed spatiotemporal delivery of transforming growth factor (TGF)- β 3 and connective tissue growth factor (CTGF) [35,36]. The 100 mg doses of growth factor-embedded microspheres resulted in increased intermediate zone type II collagen and aggrecan deposition by approximately twofold compared to the 50 mg dose when analyzing immunofluorescence images of constructs seeded with bone marrow-derived MSCs [35]. However, growth factor-embedded microsphere application decreased compressive modulus at both doses by at least twofold when compared to empty microspheres in both



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Figure 3. Tissue-Engineering Paradigm of TMJ Disc Constructs. Combination of an appropriate cell source and scaffold-based or scaffold-free approaches can be used for fabrication of a TMJ disc construct (upper panels). Via the application of various biochemical and mechanical stimuli, an enhanced, biomimetic construct can be tissue-engineered (lower panels). Abbreviations: ACs, hyaline articular chondrocytes; C-ABC, chondroitinase ABC; LBL, layer-by-layer; LOXL2, lysyl oxidase-like 2; MCs, knee meniscus cells; MSCs, mesenchymal stem cells; TGF- β , transforming growth factor β ; TMJ, temporomandibular joint.

areas analyzed [35]. Similar trends were apparent in instantaneous and relaxation moduli indicating that mechanical properties did not necessarily trend with growth factor application and ECM content [35]. Compared to traditional scaffold-based approaches, 3D printing offers the ability to create regional variation which can resemble native ECM content.

Scaffold-free approaches, such as the self-assembling process [37–39], have been developed to bypass issues related [45] to scaffold degradation products, for example, acidity due to PLA degradation [46], fabrication byproducts, for example, crosslinkers and plasticizers [46], and stress shielding of cells [47]. The self-assembling process recapitulates developmental aspects of cartilage formation to generate functional neotissues with characteristics resembling those of

native tissues [45,48]. Specifically, it is the most prominent of these techniques for TMJ disc tissue-engineering because it has generated mechanically robust tissue [37]. Stimulation of self-assembled TMJ disc constructs by bioactive agents and mechanical compression resulted in values of approximately 3.5%, 2.75 MPa, and 2.25 MPa for collagen per wet weight, tensile **Young's modulus**, and ultimate tensile strength (UTS), respectively. Additional analysis of constructs created from cocultures of hyaline articular chondrocytes (ACs) and knee meniscus cells (MCs) found collagen fibril alignment reminiscent of native TMJ discs, exhibiting direction-dependent strains in finite element analysis. This was promising because it showed anisotropic tissue on par with the alignment of native tissue [38], which further substantiates scaffold-free tissue-engineering as an alternative to scaffold-based approaches.

While scaffold-free approaches do not necessarily have the flexibility of scaffold-based approaches, for example, scaffold functionalization with biomolecules, these limitations can be overcome with exogenous stimulation, which can have various effects on scaffold-free constructs such as increased mechanical properties [49,50]. In addition, variation of the cell source can also have a large influence on the eventual properties of the resulting constructs.

Cell Sources

Selection of a cell source is one of the most important considerations for TMJ disc tissue-engineering (Table 1). Options for primary cells range from native TMJ disc cells [34,51] to other cells from hyaline articular cartilage and the knee meniscus [38]. In addition, recent advances in cell expansion technologies [52–54] have allowed exploration of costal cartilage-derived cells [39]. MSCs are also heavily used [35,36,40,41,51,55–57].

Potential primary cell sources for TMJ disc tissue-engineering include TMJ disc cells, ACs, MCs, and costal chondrocytes (CCs). TMJ disc cells have been used in multiple studies [34,51], but the dearth of available, healthy tissue raises concerns for this source [58]. Thus, ACs and MCs have been considered [38]. Using AC–MC coculture with the self-assembling process resulted in a functional, anisotropic TMJ disc as discussed above [38]. With recent advances in cell expansion technologies that preserve chondrogenic phenotype [52–54], CCs might allow for either an autologous or allogeneic approach to replacing cartilages, as demonstrated previously in articular cartilage [59,60] and the TMJ disc [39]. Allogeneic CCs can be harvested from cadaveric tissue, while autologous tissue harvest procedures are conducted routinely for rhinoplasty and autologous TMJ reconstruction. Thus, existing surgical procedures may be sufficient for tissue regeneration purposes. The use of CCs can also remove or reduce donor site morbidity and virtually eliminate the potential of harvesting cells from OA tissue. When used in a hyaline articular cartilage model, CC constructs have attained a functionality index (FI; Box 1) of 55% compared to the medial condyle cartilage properties [60]. These techniques and

Box 1. FI Compares Construct Properties to Native Tissue Values

Values for biochemical content, such as overall collagen (Col) and GAG content, accompany values for various mechanical properties such as UTS, tensile Young's modulus (E^T), compressive relaxation modulus (E^r), and compressive instantaneous modulus (E). Ranging from 0 to 100%, a value of 100% represents perfect recapitulation of native values. Subscripts serve to designate native (N) or tissue-engineered (TE) values.

$$FI(TE|N) = \frac{1}{6} \left[\left(1 - \left| \frac{GAG_N - GAG_{TE}}{GAG_N} \right| \right) + \left(1 - \left| \frac{Col_N - Col_{TE}}{Col_N} \right| \right) + \left(1 - \left| \frac{E_N^i - E_{TE}^i}{E_N^i} \right| \right) \right] \\ + \left[\left(1 - \left| \frac{E_N^r - E_{TE}^r}{E_N^r} \right| \right) + \left(1 - \left| \frac{E_N^T - E_{TE}^T}{E_N^T} \right| \right) + \left(1 - \left| \frac{UTS_N - UTS_{TE}}{UTS_N} \right| \right) \right] * 100\%$$

results offer promise of an alternative source of chondrocytes that can create mechanically stable constructs for other parts of the body such as the TMJ disc.

An array of MSCs from both adult and fetal tissues have been used, as previously reviewed [61]. MSCs from various tissues (Table 1) offer an autologous or allogeneic approach and can be isolated in large quantities, making these sources clinically relevant for construct formation. Perhaps the most interesting MSCs are those derived from the synovium because they were shown to synthesize cartilage oligomeric matrix protein, link protein, and glycosaminoglycans (GAGs), similar to ACs [62]. For example, synovium-derived MSCs on fibrin-chitosan scaffolds increased type I collagen expression approximately twofold *in vitro* and ECM deposition *in vivo* as demonstrated by histological analysis when compared to pure chitosan scaffolds [40]. Progress using MSCs has resulted in morphological and biochemical biomimicry evaluated via histology, gene expression, and other biochemical assays [36,40,41,51], but future research should focus on assaying functional properties of MSC-derived constructs via mechanical testing.

The choice of cell source remains a challenge within the field of TMJ disc tissue-engineering. Lack of standardization of mechanical testing modalities makes it difficult to compare sources head-to-head and to determine if one cell source is more suitable than another. Perhaps the most important characteristic to consider when choosing a cell source is mechanical stability of the resulting tissue-engineered construct due to the dynamic joint environment.

Improvement of Mechanical Properties of TMJ Disc Fibrocartilage

The TMJ disc functions in a dynamic environment of compression, tension, and shear [63,64]. Finite element analysis shows stresses in the TMJ disc during mouth opening to be greater than 7 MPa in compression, 4 MPa in tension, and 1 MPa in shear [65]. For comparison, the hip experiences 7–10 MPa in compression and up to 18 MPa during stressful activities such as standing up [66,67]. Characterization of the native tissue should aim to define the gold standard, design criteria for tissue-engineered TMJ disc constructs; the expectation is that replicating the mechanical properties of native tissue would allow for restoration of mechanical function. Thus, to engineer constructs with physiological levels of mechanical stresses in mind, various biochemical and mechanical stimuli, and also changes in scaffold processing (Figure 3) have been developed. For scaffold-free approaches, self-assembled constructs have approached native values in mechanical properties due to synergistic effects of biochemical and mechanical stimulation [38,39].

A majority of recent scaffold-based studies use only biochemical stimuli to improve construct mechanical properties (Table 1). Constructs stimulated with biochemical stimuli have been previously found to exhibit native tissue structure–function relationships. For example, insulin-like growth factor I and TGF- β applied to constructs created from TMJ disc cells increased collagen synthesis by greater than 400% at 3 weeks of culture, leading to higher aggregate moduli of 5 kPa [68]. However, constructs sometimes do not follow native tissue structure–function relationships [35] (e.g., increased matrix deposition leading to increased mechanical properties). To overcome such deficiencies, mechanical stimulation may be considered. However, mechanical stimulation has not been used in scaffold-based TMJ disc approaches, although it has been used in other fibrocartilages such as the knee meniscus. For example, hydrostatic pressure combined with TGF- β 1 led to fourfold higher collagen deposition and threefold higher GAG deposition, as compared to the unpressurized growth factor controls in MC-seeded PLA scaffolds [69]. Studies showing recapitulation of native tissue structure–function relationships should serve as models for future studies toward identifying additional

stimuli. Biochemical stimuli must continue to be investigated, but, additionally, mechanical stimuli can be used to increase mechanical properties of engineered discs to withstand the dynamic *in vivo* environment.

Scaffold-free approaches have combined biochemical and mechanical stimuli to generate stiffer, stronger, anisotropic constructs, followed by examination of the resulting constructs in large animal models. Using a scaffold-free approach with AC–MC coculture, TGF- β 1, chondroitinase ABC (C-ABC), and lysyl oxidase-like 2 (LOXL2) have been identified in the past as efficacious for fibrocartilage tissue-engineering, enhancing tensile Young's modulus and UTS by 245% and 186%, respectively [70]. In a self-assembled TMJ disc model using AC–MC coculture stimulated with only TGF- β 1 and C-ABC, tensile Young's modulus, UTS, and collagen per wet weight increased by twofold or greater in the intermediate zone of the disc, as compared to controls [38]. Passive axial compression and these biochemical stimuli were combined and noted to exhibit synergism, showing 5.8-, 14.7-, and 13.8-fold increases in collagen per wet weight, tensile Young's modulus, and UTS, respectively, compared to unstimulated controls [38]. Moving to *in vivo* studies, TMJ discs engineered using all three stimuli (TGF- β 1, C-ABC, and LOXL2) coupled with passive axial compression, yielded an FI (Box 1) of 42% of native properties with a passaged, allogeneic CC source [39]. By combining these three biochemical stimuli with mechanical stimulation, increased functional properties were achieved as compared to either alone. Thus, further synergistic effects of other biochemical and mechanical stimuli should be explored.

As reviewed elsewhere [49], strategies for other tissues, such as hyaline articular cartilage, can help inform further mechanical improvement of constructs. Similar designs and models can be used to engineer the fibrocartilage of the TMJ disc. For example, in a recent study on tension and its effects for articular cartilage engineering, continuous stimulation combined with a bioactive regimen increased the tensile properties by 5.8-fold over unstimulated controls in AC-derived, self-assembled constructs [71]. By improving mechanical stability using biochemical and mechanical stimuli, constructs continue to approach native tissue values. Attaining mechanical biomimicry is a crucial characteristic for constructs to perform satisfactorily when implanted into the orthotopic environment.

Current Animal Models

Prior to human clinical trials, tissue-engineered implants should be examined in relevant animal models to demonstrate initial safety and efficacy. Similar to TMJ disc tissue-engineering, development of animal models is based on design criteria. For the TMJ, similar anatomy, chewing patterns, and diets compared to humans, and ease of surgical access are included in the design criteria. In addition, relative size of TMJ structures and animal cost may also determine which model to use. Animal models exist for various purposes such as observing the adverse reactions to an implant subcutaneously to examining surgically induced pathologies in orthotopic studies. Small animals such as mice and rats are economical, serve as pain models [72,73], and simulate OA and associated degenerative changes in the joints [74,75]. However, their small TMJ disc size limits studies to simple subcutaneous implantation as opposed to orthotopic studies in larger animals such as rabbits [43]. Moving toward orthotopic studies, rabbits allow for additional biochemical and histological analysis, and reliable mechanical testing [42], but present substantial differences from human size and loading conditions [43]. This motivates the use of large animal models that more closely resemble human anatomies and conditions [42].

Many preliminary studies involve subcutaneous implantation to examine possible adverse reactions and establish proof-of-concept. These studies, as reviewed [43], are commonly

performed in mice or rats due to their low cost, without much consideration of anatomical or dietary similarities. For example, a fibrin–chitosan scaffold with synovium-derived rat MSCs was embedded into explanted TMJ discs with perforation defects and implanted into nude mice subcutaneously in a xenogeneic approach [40]. Histological analysis showed increased type I and II collagen deposition in the fibrin–chitosan scaffold, compared to the pure chitosan scaffold [40]. Although this study represents a disc perforation model, additional biochemical and mechanical analyses must be performed in larger animals to show reparative ability in the fully loaded orthotopic environment.

Recent studies used rabbits for orthotopic evaluation of tissue-engineered TMJ discs [36,41]. For example, 3D printed PCL–PLGA microsphere scaffolds seeded with allogeneic, synovium-derived MSCs were implanted into the disc and noted histologically to degrade by 6 weeks [36]. Cells retained their chondrocyte-like phenotype *in vivo* [36]. Scoring of the condylar surfaces with an **OA score** resulted in values of approximately 3.9 and 2.4 for the scaffolds without and with growth factors, respectively, where a lower score represents a better outcome [36]. While these studies [36,41] demonstrate feasibility for implantation of tissue-engineered TMJ discs via histological analysis, mechanical testing is of paramount importance to show the integrity of tissue-engineered constructs.

Strides in animal studies are promising to the research community as they point to a feasible translation pathway for tissue-engineered constructs. The use of ectopic small animal and larger orthotopic models (e.g., mouse and rabbit models) is a crucial first step in proof-of-concept work for the field. However, it will ultimately be regenerative studies in orthotopic animal models in species such as the minipig that will be most impactful for translation of tissue-engineered TMJ discs toward human clinical studies.

Path to Translation

Translational hurdles that remain include tuning of construct mechanical properties toward biomimicry (Figure 3) as well as scale-up of area and thickness of implants (Figure 4, Key Figure). A recent minipig study, showing safe and efficacious implantation of TMJ constructs [39], establishes this orthotopic large animal model as a cogent element in the translational pathway (Figure 4). Clinical and regulatory hurdles are also significant for translation of TMJ disc constructs (Figure 4).

Application of Proper Tissue-Engineering Parameters for Tuning of TMJ Disc Constructs to the TMJ Mechanical Environment

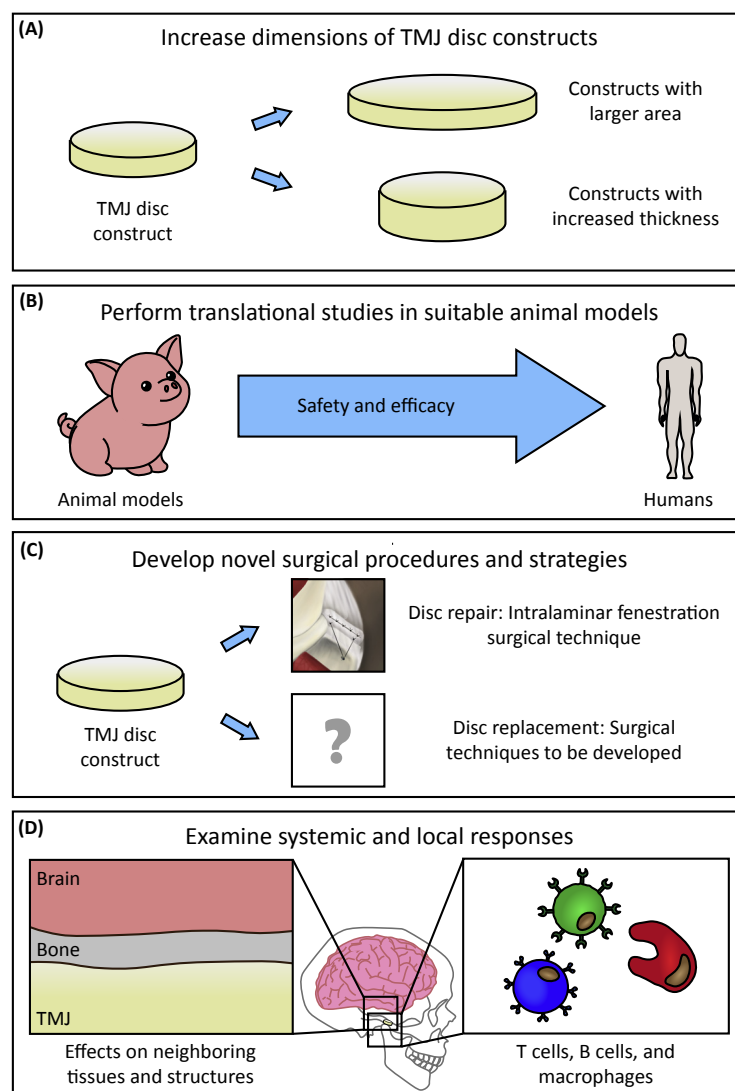
Constructs must be tuned to the mechanical environment of the TMJ disc because they will be subject to compressive, tensile, and shear forces [63,64]. Theoretically, the required mechanical properties will depend on surgical technique, model, and animal. For example, it was shown that an FI (Box 1) of 42% was sufficient when implanted via the intralaminar fenestration surgical technique (Figure 5) in a focal thinning model in the Yucatan minipig [39]. When moving toward perforation or larger defects, this implant might be insufficient. In contrast, some constructs might be too stiff or strong compared to native values, as observed in some scaffold-based approaches [35], causing stress concentrations and possible degeneration on the articulating surfaces. Also, a mismatch in the rates of scaffold degradation versus tissue formation can lead to failure. Therefore, it is important to consider tuning mechanical properties by application of proper stimulation regimens, whether using a scaffold-based or scaffold-free tissue-engineering approach (Figure 3).

Tailoring of Tissue-Engineered TMJ Discs to Human Discal Pathologies and Size

As the translational direction points to additional large animal orthotopic studies before human clinical trials commence, defect models must increase in size. As such, constructs must also

Key Figure

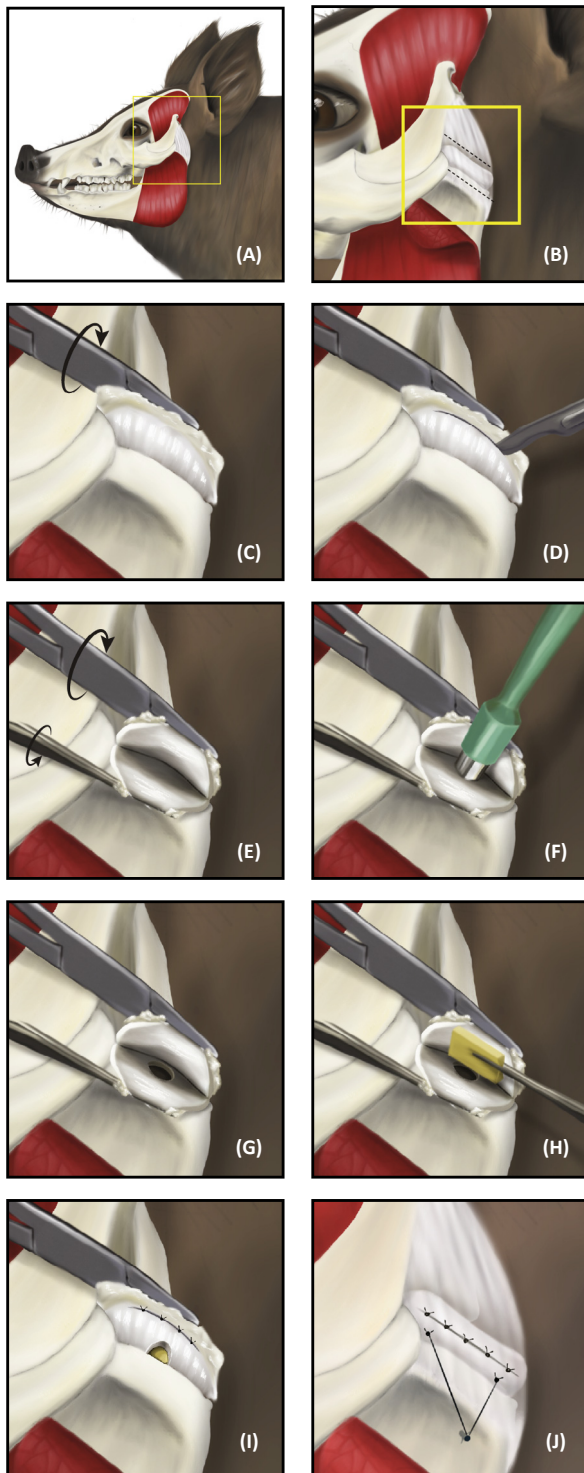
Toward the Path to Translation



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Figure 4. For a Figure360 author presentation of Figure 4, see the figure legend at <https://doi.org/10.1016/j.molmed.2018.12.007>.

(A) Constructs should be tailored for human discal pathologies and size, potentially increasing in both area and thickness. (B) Prior to translation through regulatory bodies such as the FDA, animal studies must be performed in proper large animals, such as the minipig. (C) Novel surgical procedures for disc repair and disc replacement need to be developed as well. (D) Additional studies also need to be performed to examine local and systemic responses to tissue-engineered TMJ discs in the orthotopic environment. Upon overcoming these hurdles, the TMJ disc tissue-engineering field will be closer to human clinical trials. Abbreviations: TMJ, temporomandibular joint.



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Figure 5. The Intralaminar Fenestration Surgical Technique. (A, B) Through a preauricular incision, the temporomandibular joint (TMJ) was exposed. (C–E) Surgeons filleted the disc open with a scalpel, and (F, G) created a one-sided

(See figure legend on the bottom of the next page.)

scale-up (Figure 4). In the recent minipig study [39], a one-sided, 3 mm defect, mimicking disc thinning, was used. Future studies need to scale-up to a larger defect area to mimic increased disc thinning, in addition to two-sided defects to mimic disc perforation. To scale-up constructs to larger thicknesses, one might consider using larger scaffolds. However, as scaffolds and constructs trend upward in thickness, it should be kept in mind that diffusion limitations increase. Decreased diffusion can result in shell-like neotissues with necrotic centers, that display inadequate mechanics. However, scaffold-free approaches might prove advantageous for creation of larger constructs to mimic disc thinning. Self-assembled articular cartilage constructs made of passaged ACs up to 25 mm in diameter have been made by combining cytochalasin D, TGF- β 1, C-ABC, and LOXL2, under a compressive load and in mechanical confinement [76]. This approach may allow for examining TMJ disc healing in larger defects that mimic clinically observed disc thinning. As such, a significant portion of future TMJ disc studies should investigate the scale-up of defects and constructs for relevance to human TMJ anatomy.

Novel and Cogent Translational Studies

Orthotopic large animal models need to be performed to examine the safety and efficacy of tissue-engineered constructs prior to translation. Toward selection, possible species for performing regenerative studies include sheep [77], goats [78], dogs [79], farm pigs [80], and minipigs [81]. The farm pig and minipig are two suitable models that have been recently used for regenerative studies due to their similarities to humans in chewing patterns, diet, and anatomy [3,81–85].

In a recent study demonstrating safety and efficacy of a self-assembled, allogeneic, tissue-engineered implant for disc repair, a novel TMJ disc thinning model was created in the Yucatan minipig [39]. Because the implants were created from a CC source, implantation into the TMJ disc represented nonhomologous use. Implants approaching native tissue values were stimulated by a regimen of biochemical and mechanical stimulation. To affix implants securely, the intralaminar fenestration surgical technique was developed [39] (Figure 5). Although this was an allogeneic, nonhomologous use which has potential to elicit an immune response, implant safety was shown by minimal to no immune response to the constructs, as assayed by histological staining for CD3, CD20, and CD68 for T cells, B cells, and macrophages. However, it was specified that additional work needs to further elucidate the immunological response [39], such as macrophage activation due to tissue-engineered implants [86–88] (Figure 4). In terms of efficacy, results showed that the tensile Young's modulus, integration at the repair-to-native tissue interface, and percent of defect closure were 3.4-, 3.2-, and 4.4-fold higher, respectively, compared to empty defect controls [39]. OA scores of the condylar surface treated with implants were threefold less than the empty defect controls [39], yielding a better clinical outcome overall. Together, these results demonstrate the feasibility of allogeneic TMJ disc tissue-engineered constructs in the orthotopic environment and pave the way for additional orthotopic large animal studies and future human clinical trials (Figure 4).

Overcoming Additional Clinical and Regulatory Hurdles

In stark contrast to diarthrodial joints such as the knee, there is limited knowledge surrounding the TMJ, especially when it comes to developing new processes and products for repair or replacement of the TMJ disc. Compared to the TMJ, a greater variety of products, treatments,

thinning defect via a biopsy punch. (H) A tissue-engineered disc was placed between the two laminae and (I) sutured back together. Sutures attached to the side of the disc instead of on the articulating surfaces allowed for continued loading of the TMJ disc while healing; this placement avoided possible stress concentrations and resulting degeneration. (J) The lateral attachment was recreated by use of an anchoring system. Reprinted, with permission, from [39].

and studies exist for the knee. To illustrate these differences, one can consider indications and contraindications in the TMJ versus the knee. For example, in the knee, there are clear guidelines as to what constitutes small, large, partial-thickness, and full-thickness defects with concomitant treatment algorithms [89]. In contrast, it is not clear when a tissue-engineered treatment would be indicated in the TMJ. Currently, in the knee, tissue-engineered products are contraindicated for the OA milieu [90]. This has not been confirmed for the TMJ, although the expectation is that the constructs under OA conditions might succumb to the same fate as the native tissue [91]. Development of treatment guidelines and additional studies specific to the TMJ should continue, toward bringing TMJ-related knowledge to levels of other diarthrodial joints.

One must also consider fixation and associated surgical approaches. The intralaminar fenestration surgical technique (Figure 5) was successful in treating early-stage disc thinning, but in the minipig [39]. However, in 5% of TMD cases requiring surgery [26], it is not yet obvious how one may be able to attach a partial or whole, tissue-engineered disc (Figure 4). Surgeons and researchers must continue to collaborate to develop surgical approaches for implantation of tissue-engineered implants, as they are of utmost importance to the success of the tissue-engineered treatment.

With regard to clearing the regulatory hurdle, proximity of the TMJ to the brain (Figure 4) may necessitate more stringent safety requirements than products for other joints such as the knee. These requirements may include analysis of the synovial fluid in the TMJ, but also the neighboring cerebrospinal fluid. Notoriously, mechanical failure and resulting degradation of the Proplast–Teflon disc implants resulted in exposure of the brain cavity [92–94]. Additionally, current large animal work has yet to investigate fully the immunological implications related to TMJ disc implants (Figure 4) or how immunomodulation may be used in a proinflammatory environment [95]. In terms of regulation, the US Food and Drug Administration (FDA) has not previously guided a tissue-engineered TMJ disc product [96], thus raising the question of establishing TMJ-specific safety and efficacy guidance documents. Future research in the field needs to establish the safety of tissue-engineered TMJ discs by elucidating the immune response. Additionally, researchers need to communicate with regulatory bodies, such as the FDA, to obtain guidance on how tissue-engineered TMJ disc products need to be demonstrated as safe and efficacious.

Concluding Remarks

While recent advances propel TMJ disc tissue-engineering forward, many hurdles still exist. To summarize, the pressing challenges include improvement of mechanical properties of constructs, scale-up of implant dimensions, determination of indications for tissue-engineered discs, development of surgical techniques, analysis of the immunological response, and regulation by the FDA (see Outstanding Questions). Tissue-engineering and basic science investigations for TMDs will continue to drive the field. The field should focus toward addressing questions in the clinical and regulatory spaces. Specifically, studies should pay attention to developing novel surgical techniques and associated fixation methods toward human clinical trials. For each new tissue-engineering approach, regulatory requirements need to be satisfied by demonstration of TMJ-specific safety and efficacy in large animal models. As regulatory bodies turn their attention toward clinical trials, these data will be the primary preclinical assessment of implants. Considering the momentum toward significant preclinical studies, it is an exciting time to be in the field of TMJ disc tissue-engineering. After the early success shown in the orthotopic study performed in the Yucatan minipig [39] and the identification of clinical and regulatory hurdles discussed here, there is new impetus to develop tissue-

Outstanding Questions

How do researchers achieve tuning of tissue-engineered constructs to the mechanical environment of the TMJ disc?

Can researchers scale-up constructs, in area and thickness, to be relevant to human discal pathologies and size?

For what cases will tissue-engineered products be indicated (or contraindicated)?

Can novel surgical procedures be developed for accessing the TMJ, and fixing and implanting tissue-engineered TMJ disc constructs orthotopically?

What are the local and systemic responses to tissue-engineered TMJ discs *in vivo*?

How would tissue-engineered constructs for the TMJ disc be regulated by the FDA?

engineering solutions to begin addressing the various intractable TMJ trauma and degenerative ailments. The possibility of translating tissue-engineered TMJ discs is increasingly being realized.

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