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Biomechanics of Meniscal Allograft Transplantation: A Meta-Analysis

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SUMMARY

Introduction. Despite trends to repair meniscal defects, meniscectomy continues to be a common procedure. Degenerative changes following these surgeries become candidates for meniscal allograft transplantation.

Purpose. The purpose of this meta-analysis was to review published articles that compared methods of meniscal allograft transplantation (bone plug, suture only, or bone bridge) for their biomechanical effects on tibiofemoral mean contact pressure and contact area in relation to intact meniscal states.

Materials and methods. PubMed database search on July 15, 2020 for articles evaluating the knee kinematics of MAT in a biomechanical model.

Results. The greatest contact area was found in the setting of an intact meniscal state, with a mean difference of 188.886 mm^3 (95%CI 148.059-229.672, $p < 0.001$) and 78.713 (95%CI 78.713-103.733, $p < 0.001$), when compared to meniscectomy and MAT respectively. Although MAT showed a lower contact area *vs* the intact knee, it did have a greater contact area than meniscectomy by 94.951 mm^2 (95%CI, 71.590-118.312, $p < 0.001$). The dovetail bone bridge technique was shown to have the highest difference in mean contact area of 207.676 mm^2 (95%CI 85.288-330.065, $p < 0.001$) when compared to bone plug technique.

Conclusions. Meniscal allograft transfer demonstrated significantly less contact area than a meniscus intact knee and significantly higher contact area than meniscectomy. In the systematic review, bone bridge meniscal allograft transplant techniques offered the closest reproduction of native knee biomechanics when compared to bone plug and suture only.

KEY WORDS

Meniscal allograft transplant techniques; biomechanics; contact area; meniscus; meniscectomy.

INTRODUCTION

The meniscus is a fibrocartilaginous tissue that reduces tibiofemoral contact forces by increasing joint congruency. Additionally, it serves as a source of proprioception, nutrition, and lubrication (1-4). Originally described by Fairbanks, complete meniscectomy rapidly increased the rate of osteoarthritis within the knee. Indeed, it is well established in the literature that meniscal deficiency leads to mechanical knee degeneration (5-9). Although there have been more recent trends to preserve the damaged meniscus with repair techniques, meniscectomy continues to be a commonly employed procedure when repair is not feasible (10-14). Certain tear morphologies consisting of flaps, radial tears, and large degenerative tears are largely considered irreparable (15, 16). Unfortunately, these injuries frequently leave patients with subtotal or total meniscectomy. Young patients with symptomatic degenerative changes following these surgeries become candidates for meniscal allograft transplantation.

Since the original case series by Milachowski *et al.*, meniscal allograft transplantation (MAT) has become an acceptable method of treating young patients with challenging meniscal deficiency. MAT success is dependent on numerous variables: graft size, knee stability, degree of arthrosis, axial alignment, rehabilitation protocol, and obesity. Recent studies have shown fair to excellent outcomes, second look arthroscopies have demonstrated healing to the peripheral rim, and some series have shown 70% clinical survivorship at 10 years postoperatively (2, 17-22). The most important surgeon controllable factor is the method of MAT fixation. To date there exist three methods of MAT: 1) dovetail bone bridge fixation - in which the posterior and anterior horns of the graft remain connected to a single piece of bone, 2) bone plug fixation – in which 2 separate osseous segments are attached to the posterior and anterior horns, 3) suture only – in which the meniscal allograft is tethered to the meniscocapsular rim via suture fixation. Various studies have demonstrated alteration in joint contact forces with these different fixation techniques; however there remains no literature directly comparing these methods across studies (18-20, 22-27).

The purpose of this meta-analysis was to review published articles that compared methods of meniscal allograft transplantation (bone plug, suture only, or bone bridge) for their biomechanical effects on tibiofemoral mean contact pressure and contact area in relation to intact meniscal states.

MATERIALS AND METHODS

There were no ethical concerns for this meta-analysis of biomechanical articles.

Article screening

We searched the PubMed database on July 15, 2020 for articles evaluating the knee kinematics of MAT in a biomechanical model. The search field was entered as: ("Meniscus allograft"[All Fields] OR "Meniscal allograft"[All Fields] OR "meniscus allograft transplant"[all fields] or "meniscal allograft transplant"[all fields]) AND ("Biomechanic"[All Fields] OR "Biomechanics"[All Fields] OR "Biomechanical"[All Fields] OR "cadaver"[all fields]). Two authors (BC and KP) independently screened the resulting 85 articles for inclusion or exclusion using Abstrackr software (Brown, Providence, RI). Disagreements were reviewed by the lead author (SK) who made the final decision whether to include or exclude the references. Inclusion criteria were biomechanical studies of MAT on human cadavers that reported mean contact area, mean contact pressure, mean peak contact pressure in native, total meniscectomy states as well as following MAT. Initial screening following a review of disagreements resulted in 15 articles for full review. The sources of these articles were reviewed and cross-referenced with the 85 original articles. Five additional articles were added to the full text review while seven were excluded for different reasons such as only reporting translation/strain forces, pull out strength, extrusion values and lack of mean and standard deviation values. Subsequently 12 articles were included in the study. These articles were then evaluated for quality using the Quality Appraisal for Cadaveric Studies (QUACS) scale, which is a validated means for assessing the quality of cadaveric studies.

Data collection and included studies

Data was collected from each including: sample size, mean contact pressure, mean peak contact pressure, mean contact area, MAT fixation type, force applied during testing, MAT location (medial *vs* lateral) and graft type.

The included studies were Ambra, Brial, Dienst, Huang, Huang, Kim, McDermott, Paletta, Sekaren, Vrancken, Wang.

RESULTS

The results of the meta-analysis showed that the greatest contact area was found in the setting of an intact meniscal state, with a mean difference of 188.886 mm^3 (95%CI 148.059-229.672, $p < 0.001$) and 78.713 (95%CI 78.713-103.733, $p < 0.001$), when compared to meniscectomy and MAT respectively. Although MAT showed a lower contact area *vs* the intact knee, it did have a greater contact area than meniscectomy by 94.951 mm^2 (95%CI, 71.590-118.312, $p < 0.001$) (**table I**).

Regarding mean contact pressure and mean peak contact pressure, meniscectomy had greater pressures *vs* MAT by 0.506 MPa (95%CI 0.351-0.660, $p < 0.001$) and intact states by 0.751 (95%CI 0.549-0.952, $p < 0.001$). MAT also was noted to have a greater mean contact and mean peak contact pressures than intact states by 0.239 Mpa (95%CI 0.145-0.332, $p < 0.001$) (**table II**).

Meta-regression showed that each of the MAT techniques chosen had differing effect on contact area and contact pressures (**table III**). The dovetail bone bridge technique was shown to have the highest difference in mean contact area of 207.676 mm^2 (95%CI 85.288-330.065, $p < 0.001$) when compared to bone plug technique. There was also a greater difference of 115.250 mm^2 (95 CI 40.761-189.740, $p = 0.002$) in the contact area of soft tissue grafts in comparison to bone plug technique. Additionally, the soft tissue graft had the lowest difference in mean contact pressure of 1.018 MPa (95%CI -1.688 to -0.347, p = 0.003) less than the bone plug technique. Inconsequentially, bone plug was shown to have the lowest peak contact pressure of 5.525 MPa (95%CI 4.923-6.126) with differences between dovetail and soft tissue graft being 2.074 (-0.027 to 4.175, p = 0.053) and 0.848 (-0.347 to 2.043, p = 0.164).

Table I. Characteristics of included studies.

Lead Author	Year of Publication	Technique	Compartment	Total Sample Size	Average Age Cadavers (Years)
Ambra	2019	Bone plug *vs* suture only	Medial	9	46.9
Brial	2019	Bone bridge *vs* bone plug	Lateral	6	Not Reported
Dienst	2007	Bone bridge	Lateral	6	66 (49-79)
Huang	2002	Bone plug	Lateral	15	52
Kim	2012	Suture only	Medial	10	54 (42-61)
McDermott	2008	Bone bridge *vs* suture only	Lateral	5	89
Paletta	1997	Bone plug	Lateral	10	22-47 (avg not reported)
Sekaren	2002	Bone Plug	Medial	8	56 (38-70)
Vrancken	2014	Suture only (PCU *vs* allograft)	Medial	5	70-88
Wang	2014	Bone plug *vs* suture only	Medial	7	Not Reported
Alhalki	2000	Bone Plug (Allo *vs* Auto)	Medial	10	70
Alhalki	1999	Bone plug *vs* suture	Medial	10	70

Table II. Statistical analysis.

Comparison	Difference in Mean Contact Area (mm^2) (95%CI)	P value
Intact *vs* Meniscectomy	188.866 (148.059-229.672)	< 0.001
MAT *vs* Meniscectomy	94.951 (71.590-118.312)	< 0.001
Intact *vs* MAT	78.713 (53.694-103.733)	< 0.001
	Difference in Mean Contact Pressure (MPa) (95%CI)	
Meniscectomy *vs* Intact	0.751 (0.549-0.952)	< 0.001
Meniscectomy *vs* MAT	0.506 (0.351-0.660)	< 0.001
MAT *vs* Intact	0.239 (0.145-0.332)	< 0.001
	Difference in Mean Peak Contact Pressure (MPa) (95%CI)	
Meniscectomy *vs* Intact	2.730 (1.850-3.610)	< 0.001
Meniscectomy *vs* MAT	1.129 (0.538-1.720)	< 0.001
MAT *vs* Intact	1.676 (0.869-2.482)	< 0.001

Table III. Meta regression.

Contact Area (mm^2)
Bone plug 248.336 (209.345-287.328)
Dovetail +207.676 (85.288-330.065) p < 0.001
Soft tissue +115.250 (40.761-189.740) p = 0.002
Medial 377.123 (328.865-425.381)
Lateral -146.367 (-210.082 to -82.651) p < 0.001
All MATs medial and lateral
Mean Contact Pressure
Bone plug 2.213 (1.876-2.550)
Dovetail -0.923 (-2.662-0.816) p = 0.298
Soft tissue -1.018 (-1.688 to -0.347) p = 0.003
Medial 1.297 (0.938-1.656)
Lateral +1.239 (0.733-1.746) p < 0.001
Peak Contact Pressure
Bone Plug 5.525 (4.923-6.126)
Dovetail +2.074 (-0.027-4.175) p = 0.053
Soft tissue +0.848 (-0.347- 2.043) p = 0.164
Medial 5.125 (4.301- 5.949)
Lateral +1.177 (0.132-2.222) p = 0.027

DISCUSSION

Main findings of our paper

Intact vs MAT vs meniscectomy and purpose of meta-analysis

In agreement with prior literature on the topic, the meniscal allograft transplant does not restore knee biomechanics to a native state (2, 18, 20, 22, 24, 28). When compared to complete meniscectomy, meniscal allograft transplant in our review demonstrated improvement in contact area by 94.9 mm^2, which corresponded to a decrease in both mean contact pressures and mean peak pressures by 0.506 and 1.129 MPa – respectively. These findings reinforce that MAT improves knee biomechanics by increasing contact area. Although the contact area and pressures after MAT more closely approach those of an intact knee state, there remains a statistically significant difference when compared to an intact knee. These findings support the significant role of the meniscus as a load distributor within the knee and explains the correlation between degenerative changes and meniscal deficiency (13, 29-32). Additionally, Zaffagini *et al.* found that knee laxity was reduced following MAT compared to the pre-operative state, indication a role for MAT in improving the biomechanics of the knee (33). As the body of evidence on meniscal allograft transplantation continues to grow, the gap between biomechanics of the meniscal transplanted knee and native knee may continue to shrink (1, 22, 24, 25).

The 12 high-quality biomechanical studies included in our systematic review determined that meniscal allograft transplantation through a dovetail bone bridge graft technique was shown to have a statistically significant higher contact area than bone plug and suture only techniques. Furthermore, the mean peak contact pressures encountered through bone plug techniques were lower than both dovetail and soft tissue techniques, although the difference between bone plug and soft tissue was not statistically significant. These are important variables to take into consideration when discussing surgical indications and techniques for meniscal allograft transplantation (2, 24). A pitfall of any MAT procedure is the size of the chondral defect, which is difficult to remedy no matter the technique. Steadman microfracture technique aims to fill the chondral defect with stable clot, thereby providing an ideal environment for repair. This technique has been shown to be effective in the management of high-grade chondral defects with great clinical outcomes at 11-year follow-up (34). No biomechanical studies have been performed to assess whether Steadman microfracture technique is able to restore knee biomechanics to a native state. The authors feel future research should target this question.

Contact area

Upon meta regression, meniscal allograft transplantation through dovetail bone bridge technique had the greatest increase in compartment contact area compared to traditional bone plug by 207.676 mm^2 (95%CI 85.288-330.065) $p < 0.001$) and soft tissue grafts by 115.250 mm^2 (95%CI 40.761-189.740) $p = 0.002$). Although these values still significantly fell short of the native knee by an average of 78 mm^2.

In comparison to previous literature, our results corroborate the role of boney techniques in achieving rigid fixation of both the anterior and posterior horns – particularly the dovetail MAT, which was closest to restoring contact area in comparison to an intact knee. For example, Ambra *et al.* was not able to demonstrate significant difference in mean contact area between MAT with bone plug and native knee states, but suture only fixation was significantly associated with reduced contact area compared to native knee state within 0-30 degrees of flexion (28). Similarly, Wang *et al.* showed MAT via bone plugs resulted in increased contact area that more closely resembled native knee state than with MAT via suture only fixation (38). These differences in contact area from varying MAT techniques are likely the result of the degree of meniscal extrusion throughout dynamic knee activities. In fact, rigid fixation is an essential tenet to avoid meniscal extrusion under increasing axial loads (35). While technically easier, it remains controversial if soft-tissue-only fixation is comparable to boney techniques, as few biomechanical studies exist directly comparing the two (28). For example, one series citation found suture only to have a lower contact area than bone plug, but the difference was not statistically significant (36). Additionally, Alhalki *et al.* demonstrated no significant difference in medial knee contact area compared to native knee after MAT with bone plug or with suture (36).

Mean contact pressure/peak contact pressure

Our values for peak contact pressure correlate with established literature. Alhalki *et al.* showed that neither MAT with bone plug nor MAT with suture reconstituted normal medial knee peak contact pressures; however, normalized peak pressures were significantly higher when using a suture only technique. Furthermore, mean pressures were not significantly different from MAT with bone plug *versus* normal knee states, but were significantly greater with suture only technique (49-61% increased pressure throughout knee ROM 0-45 degrees) (36). McDermott *et al.* was not able to demonstrate a significant difference in peak contact pressures between MAT via bone block or MAT via suture compared to native knee states; however, direct comparison of peak pressures showed significant increase in suture only compared to bone block techniques (32). Similarly, Wang *et al.* and Ambra *et al.* demonstrated closer approximation of native knee contact and peak contact pressures with bone plug techniques as compared to soft tissue techniques.

Interestingly, meta regression revealed mean contact pressures were lowest with soft tissue techniques by 1.018 Mpa ($p = 0.003$) compared to bone plug and no significant difference between either of the boney techniques. These findings, however, are likely contributed to the great heterogeneity within studies. Of the 12 included studies for meta-analysis, only 4 directly compared boney to soft tissue procedures (28, 32, 36, 38), while 2 reported values exclusively for suture techniques (30, 39). Sub stratification of compartmental peak contact pressures by MAT technique demonstrated lowest pressures with bone plug (5.525 MPa) technique, which was not statistically different from dovetail (7.599, $p = 0.053$) or soft tissue techniques (Mpa = 6.373, $p = 0.164$).

Biomechanical comparisons between MAT techniques with consideration of medial vs lateral compartments

Direct comparison of medial *versus* lateral compartments after MAT did demonstrate that medial compartment more frequently had greater contact area, lower contact pressure, and lowest peak contact pressures. These results are consistent both with prior literature and native knee biomechanics. For example, Devaraj *et al.* discussed that the ability of the medial condyle to withstand greater forces is due to the more constrained medical meniscus as it is attached to the MCL (37). This necessitates a greater contact area as the medial condyle functions as the central point of pressure during the knee is in extension. Dynamically, when flexion is involved, the medial meniscus posteriorly carries loads during the early stance phase of walking. Because the asymmetric C-shape, the anterior portion of the medial meniscus is much thinner anteriorly and less readily absorbs the joint load compared with the posterior area (38). This inherently makes direct comparison of soft tissue techniques in the lateral meniscus more challenging.

The previous literature in consideration of the lateral compartment, has predominately focused on the biomechanical advantages that can be gained. It has been postulated that in order to gain biomechanical advantage with a MAT procedure, the circumferential distribution of axial loads by the menisci must be taken into account. This particularly applies to the allograft attachment to the anterior and posterior meniscal horns (40). Due to the proximity of the anterior and posterior horns of the lateral meniscus, some authors favor bone bridge fixation of the lateral compartment while more variability exists in medial compartment techniques (41).

Limitations

Anatomic meniscal allograft transplantation is a challenging procedure requiring technical precision. Indeed, it has been demonstrated in cadaveric studies that nonanatomic placement exceeding 5 mm has dramatic effects on contact pressures (42). This bears reason on clinicians frequently using size matched transplants when performing these procedures but was not the case for the studies mentioned. These cadaveric studies were frequently performed in a manner where external validity of accurate horn positioning was not always possible. This also brings into question the difference in protocols for each study and the lack of control groups used within.

The precise relationship between contact stress and area to articular cartilage longevity has not been determined (43). Numerous clinical studies have been published demonstrating a variety of surgical techniques and their clinical outcomes but still have not highlighted a particular advantage of boney to suture technique (26, 27, 44-47). Nonetheless it is generally regarded that biomechanical forces withstood by the tibiofemoral surface plays an important role in joint degradation (48-50). It should also be noted that despite any biomechanical limitations of MAT, graft survivorship at 10 years has been shown to be as high as 89% (51).

CONCLUSIONS

In conclusion, this meta-analysis showed that meniscal allograft transfer demonstrated a significantly higher contact area than meniscectomy. However, it still had significantly less contact area than a meniscus intact knee. Consequentially, to reduce biomechanical burden through improving MAT techniques, we sought to better elucidate which is optimal among the three current methods of MAT: dovetail bone bridge, bone plug, and suture only. In this systematic review, dovetail bone bridge meniscal allograft transplant techniques offered the closest reproduction of native knee biomechanics with the significantly highest mean contact area. Although this cadaveric biomechanical evidence suggests an advantage in reproduction of native knee biomechanics with boney techniques in MAT, the clinical studies thus far do not demonstrate superiority with any technique. Further prospective study is necessary to understand the effects of MAT on native biomechanics.

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None.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

SK, KP, BC: data collection, writing - original draft, writing - review & editing. NR: writing - original draft, writing - review & editing. EH: data analysis, writing - original draft, writing - review & editing.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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