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Surgical Techniques of, and Outcomes after, Distal Muscle Stabilization in Transfemoral Amputation: A Systematic Review and Narrative Synthesis

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Background: Distal muscle stabilization, such as myodesis (suturing muscles to bone) or myoplasty (suturing agonistic-antagonistic muscles together), can aid residual limb stabilization, provide a good soft-tissue covering, and increase rehabilitation potential. However, surgical practice varies due to scant clinical data. The aim of this review is to summarize and evaluate the literature regarding techniques and associated outcomes of distal muscle stabilization in transfemoral amputation (TFA).

Methods: A systematic review and narrative synthesis was performed following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Resources, including observational studies, nonobservational scientific papers, conference proceedings, and textbooks, detailing techniques of TFA distal muscle stabilization were identified from standard medical repositories and library search. A supplementary search of YouTube and Google was undertaken to identify additional resources. Quality assessment was undertaken using Risk Of Bias In Nonrandomized Studies−of Interventions; Authority, Accuracy, Coverage, Objectivity, Date, Significance; and modified-Discern tools.

Results: Forty seven resources were identified, including 17 journal articles, 17 textbooks, 5 educational websites/eBooks, 5 videos, 2 online presentations, and 1 webpage. Thirty seven described myodesis, 11 described myoplasty, and 6 described closure without distal muscle stabilization. Eight observational studies presented outcome data for 302 TFAs. No studies comparing closure with or without distal muscle stabilization were identified. All papers describing myodesis secured the adductors to the femur, and most also secured the quadriceps and/or hamstrings to this complex. Number of femoral drill holes varied from 1 to 6. Early wound complications occurred in 17% of amputations, whereas myodesis failure occurred in 9.5%. Prosthetic fitting rates were 73% and, where reported, 100% of patients maintained neutral femoral alignment.

Conclusions: Distal muscle stabilization, particularly myodesis, is a commonly described technique for TFA, although operative techniques are heterogenous. There is a paucity of outcome data, and no studies comparing it to closures without distal muscle stabilization. However, these

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low-quality data suggest wound healing rates are equivalent to TFA without distal muscle stabilization while demonstrating improvement to patients' rehabilitation potential.

INTRODUCTION

Transfemoral amputation (TFA) is a high-risk operation with complications including muscle atrophy, surgical site infections, wound dehiscence, abduction-flexion contractures, chronic pain, and depression.[1] A key component of a functional residual limb is a well-balanced soft-tissue envelope, which can promote wound healing, preserve muscle function, and optimize rehabilitation potential, directly impacting quality of life,[2] and identified as a research priority in amputation surgery.[3] Distal muscle stabilization secures or stabilizes transected muscles during an amputation. Two methods of distal muscle stabilization are recognized: myoplasty, the suturing of agonistic to antagonistic muscles, or myodesis, the anchoring of transected muscles directly to the bone, typically via drill holes in bone.[4] If distal muscle stabilization is not undertaken, fascial closure leaves transected muscles unattached within the fascial layers.

While distal muscle stabilization would be theoretically appealing in improving patient outcomes, potential downsides do exist. These include a longer operative time,[5−7] myodesis failure,[5,8−11] iatrogenic fractures secondary to drill holes created for myodesis,[6,12] and the development of a myoplastic muscular sling.[4,13−18] Additionally, distal muscle stabilization may be less suitable in those with significant comorbidities and/or poor tissue quality, such as elderly and dysvascular patients. The Global Guidelines on the Management of Chronic Limb-Threatening Ischemia[19] states that effective prosthetic use relies on a residual limb being ‘‘created to truly function as a dynamic sensorimotor end organ’’ and that ‘‘muscle stabilizing procedures can help create a stump with its proprioception intact and any of the procedures can be used, including myoplasty, myodesis, and osteo-myoplasty’’. However, the current literature regarding distal muscle stabilization techniques and outcomes in TFA is limited, and current operative practice is heterogenous.

The aim of this review was therefore to summarize and evaluate the literature on described surgical techniques for distal muscle stabilization and fascial closure in TFA and report any associated patient outcomes.

METHODS

Search Strategy

This systematic review was undertaken, and is reported, in accordance with the Preferred Reporting Guidelines for Systematic Reviews,[20,21] and was registered prior to starting with PROSPERO [CRD42022359559].

A robust search encompassing published and gray literature was undertaken. A search strategy was designed with the support of a specialist librarian to identify publications that described surgical techniques used for distal muscle stabilization/fascial closure in TFA with or without patient outcome data (see Appendix A for full search history including MeSH terms used). The following databases were searched: MEDLINE (via OVID), Embase, and Cochrane Library. Further papers were identified using the ‘‘related articles’’ function on PubMed, and reference lists of included articles were hand-searched. A gray literature search of conference proceedings on BIOSIS, via Web of Science, and a search of the National Health Service Wales Library of the Health service to identify library textbooks. Additionally, a supplementary gray literature search was performed via YouTube and Google search engines. These widely accessed platforms are frequently used to identify educational material by surgeons, and inclusion of these gave a comprehensive review of resources accessed by current practitioners and trainees. Both sources are imperfect due to the unknown and uncontrollable search algorithms which yield high numbers of results. For example, a GoogleTM search adapts to each user, attempting to personalize results. To avoid this, searches of YouTube and Google were performed on a private browser, with all cookies deleted and logged off from all GoogleTM accounts. Results were ranked according to ‘‘relevance’’ as per the search engines algorithm. The authors limited their review to the first 50 results, by which point resources had become irrelevant, as per published guidance.[22−24] No restrictions on date, language, or publication type were applied. The last search date was October 16, 2022.

Inclusion and Exclusion Criteria

Resources suitable for inclusion included published articles, abstracts, conference proceedings, medical textbooks, YouTube videos, and educational websites (defined as an informational webpage directed at healthcare professionals) in English. Non-English papers were only included if they had an English abstract with sufficient detail to meet the inclusion criteria.

Resources that described a surgical technique for TFA with sufficient detail to ascertain if distal muscle stabilization was described/undertaken were included. Patient outcomes were not mandatory for a resource to be suitable for inclusion. TFAs undertaken for any indication, by any surgical speciality, were included.

Resources that reported other types of amputation (e.g., hip disarticulation, knee disarticulation, below-knee, and upper limb), nonhuman studies, complex reconstruction surgery, and literature focusing on the use of endo-prosthetic/osseo-integrated implants were excluded. Resources describing the technique for a TFA, but with no detail regarding closure of the fascia or muscle stabilization, were excluded.

Data Extraction and Outcome Measures

Two authors (I.F. and D.T.) performed each step (literature search, data extraction, and methodological quality assessment) of the review independently and compared results. Any disagreements were arbitrated by the senior author (D.C.B.).

A draft list of variables for data capture (both standard and gray literature) was created and refined during data extraction. Data collected included type of resource, year of publication, whether myodesis (anchoring of transected muscles directly to the bone via drill holes), myoplasty (suturing or agonistic to antagonistic muscles), or fascial closure was described, the indications to perform or not perform distal muscle stabilization/fascial closure and reported benefits or downsides, and specific technical details as appropriate (specific equipment, patient and limb positioning, musculature involved in myodesis or myoplasty, muscle attachment location to the femur, and number and location of drill holes in myodesis). When reported, outcome data of distal muscle stabilization were collected including number of patients/TFAs, operative time, early wound, postoperative pain, revision surgery, flexion deformity, rate of prosthetic use, and mortality.

Where possible, data regarding both number of patients and number of TFAs were collected to account for patients who underwent bilateral amputation.

Assessment of Quality

The Risk Of Bias In Nonrandomized Studies—of Interventions tool was used to assess study quality in observational studies.[24] For resources not reporting any patient outcome data, the Authority, Accuracy, Coverage, Objectivity, Date, Significance tool was used.[25] Supplementary resources found via YouTube and Google search were evaluated using the mDISCERN score[26] (Appendix B).

Narrative Synthesis

Outcome data were heterogenous and therefore insufficient for meta-analysis. A narrative synthesis was therefore conducted in accordance with the Guidance on the Conduct of Narrative Synthesis in Systematic Review.[27] Two authors systematically summarized the key aspects of each study's methodology and results. The senior author then identified and grouped common themes.

RESULTS

A total of 678 unique resources were found on the initial search, of which 47 resources met the inclusion criteria, including 17 papers,[5–8,12,13,18,28–37] 17 books,[4,14–17,38–49] 5 videos,[50–54] 5 educational websites/online textbooks,[1,10,49,55–57] 2 online presentations,[9,58] and 1 independent website[11] (Fig. 1).

Patient data were reported from 8 observational studies comprising of 302 TFAs. It was not possible to ascertain the exact number of patients as 1 paper[8] considered amputated limbs individually, not specifying patient numbers. Denominators for outcome data are therefore reported as number of TFAs and, where available, number of patients. Study baseline data are detailed in Table I.

Thirty-seven resources described myodesis as a technique for distal muscle stabilization.[1,4–18,28–34,36,37,40,42,44,46–49,52,55–58] Three resources[34,35,47] described an alternative method of myodesis, by which the muscles were sutured to the periosteum. Myoplasty was described in 11 resources[4,6,18,29,35,36,39,44,45,48,54,55] and fascial closure, with no distal muscle stabilization, in 7 resources.[4,38,41,43,50,51,53]

Quality Assessment and Risk of Bias

Supplementary Table 1 details the risk of bias of included observational studies; most were at high risk of bias. Many studies limited inclusion to

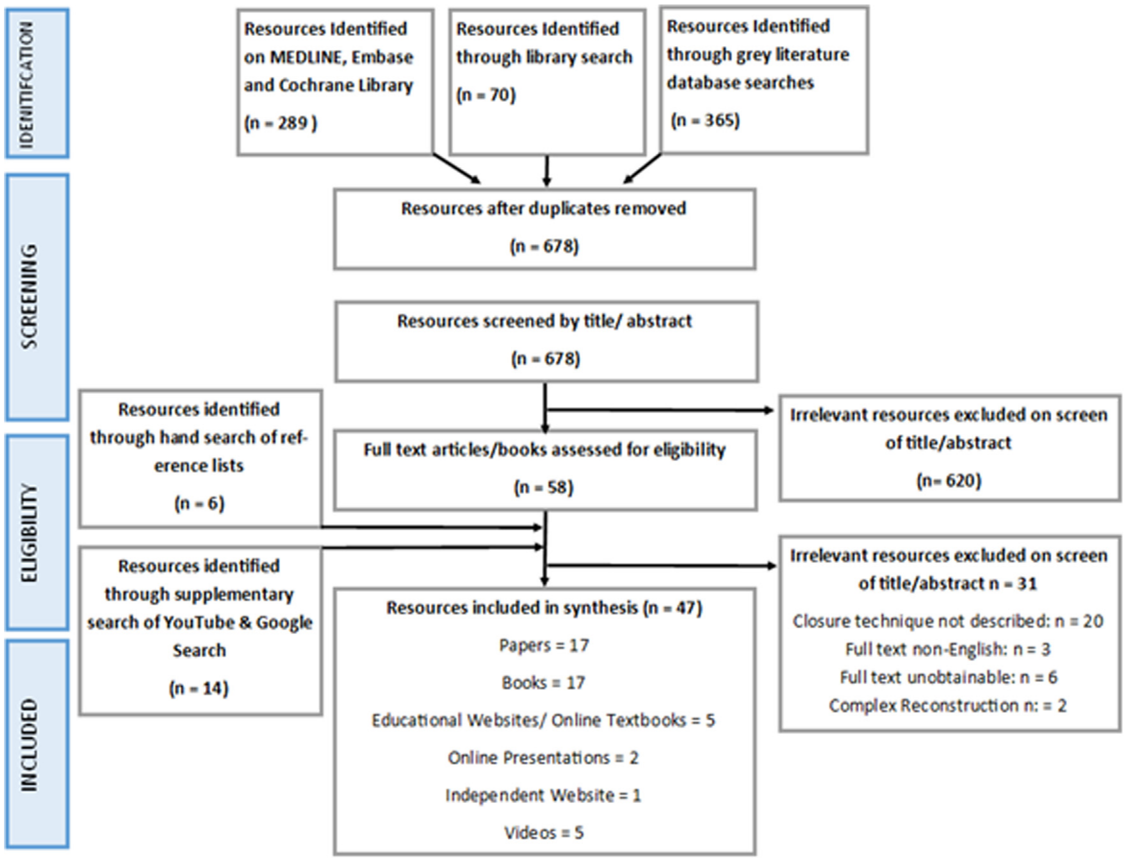

Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram.

specific indications for TFA (such as the mangled lower extremity) which reduces applicability. The overall quality of the gray literature was assessed as 'good' in the nonobservational scientific articles (Supplementary Table 2) and 'moderate' within the supplementary resources (Supplementary Table 3).

Indications and Contraindications of Distal Muscle Stabilization

No resources detailed absolute indications for distal muscle stabilization; however, 3 resources[4,5,13] suggested myodesis should be attempted in all patients. Three resources highlighted the importance of myodesis in TFAs secondary to trauma[8,37] or in elderly dysvascular patients,[12] due to the preservation of physiological muscle tension.

Seven resources described relative contraindications to distal muscle stabilization, all relating to a lack of quality or availability of the tissues required. Specifically, these were tissue loss secondary to myonecrosis, wasting or trauma,[4,5,18,42,48] tumor involvement of the distal muscles,[5,15] and (for myodesis) poor bone quality.[6] One resource stated that distal muscle stabilization is not routinely performed in amputations secondary to ischemia;[32] however, no reasoning for this statement was provided.

Technique of Distal Muscle Stabilization

Myodesis. Distal muscle stabilization by myodesis is achieved by suturing muscles and/or tendons directly to the bone, typically via drill holes made in the distal femur (Table II).

Patient positioning. Twelve resources[1,4,5,12,13,15,28,36,40,48,49,57] detailed patient positioning for the myodesis; 9 stated the ipsilateral hip should be elevated,[1,4,5,12,13,15,28,57] 7 stated the femur should be held in extension,[1,4,5,13,28,36,40] and 7 stated the femur should be in adduction.[1,4,5,13,28,36,48]

Muscles involved. Thirty-three[1,4,5,7–13,15–18,28–32,34,36,37,40,42,44,46,47,49,52,55–58] resources detailed the muscles involved in myodesis, all of which included the adductors. Twenty

Table I. Baseline demographics

Resource	Year	Design[a]	Total no. of patients in study	Total no. of TFA in study	Indication for TFA[b]	Closure technique described[c]
Hsu et al.[5]	2018	1	8	8	1, 2, 3, 4	3
Putz et al.[30]	2017	1	12	12	4	3
Konduru et al.[12]	2007	1	33	34	1	3
Gottschalk et al.[28]	1999	1	20	20	1, 2, 3, 5	3
Geertzen et al.[6]	2019	1	4	4	NS	2, 3
Zolper et al.[7]	2022	1	188	41	2	3
Ertl et al.[33]	2018	1	66	68	3	3
Tintle et al.[8]	2014	1	226	115	3	3
Gottschalk et al.[13]	2016	2	N/A	N/A	N/A	3
Jacobs et al.[31]	2011	2	N/A	N/A	N/A	3
Anderson[32]	2005	2	N/A	N/A	N/A	3
Ranz et al.[29]	2017	2	N/A	N/A	N/A	2, 3
Tintle et al.[37]	2010	2	N/A	N/A	N/A	3
Pinzur et al.[36]	2007	2	N/A	N/A	N/A	2, 3
Ertl[35]	2021	2	N/A	N/A	N/A	2, 4
Chadwick et al.[18]	1991	2	N/A	N/A	N/A	2, 3
Kalapatapu[34]	2022	2	N/A	N/A	N/A	3, 4
Lumley et al.[39]	2009	3	N/A	N/A	N/A	2
Eidt et al.[40]	2014	3	N/A	N/A	N/A	3
Hands et al.[38]	2015	3	N/A	N/A	N/A	1
Malone[41]	2006	3	N/A	N/A	N/A	1
Court-Brown et al.[42]	2006	3	N/A	N/A	N/A	3
Crawford et al.[43]	1994	3	N/A	N/A	N/A	1
Wilson et al.[44]	2017	3	N/A	N/A	N/A	2, 3
Galland et al.[14]	1994	3	N/A	N/A	N/A	3
Lamont et al.[45]	1999	3	N/A	N/A	N/A	2
Wiesel et al.[15]	2022	3	N/A	N/A	N/A	3
Yao et al.[16]	2001	3	N/A	N/A	N/A	3
Gottschalkr et al.[17]	2012	3	N/A	N/A	N/A	3
Feezor et al.[46]	2014	3	N/A	N/A	N/A	3
Eidt et al.[47]	2014	3	N/A	N/A	N/A	3, 4
Beard et al.[48]	2016	3	N/A	N/A	N/A	2, 3
Smith et al.[4]	2004	3	N/A	N/A	N/A	1, 2, 3, 4
Sugarbaker et al.[49]	2001	3	N/A	N/A	N/A	3
Myers[1]	2022	4	N/A	N/A	N/A	3
Wheeless et al.[56]	2022	4	N/A	N/A	N/A	3
Berke et al.[10]	2008	4	N/A	N/A	N/A	3
Orthobullets[57]	2016	5	N/A	N/A	N/A	3
Physiopedia Contributors[55]	2022	5	N/A	N/A	N/A	3
Maham and Diab et al.[50]	2019	6	N/A	N/A	N/A	1
MovieSurg[51]	2014	6	N/A	N/A	N/A	1
Husky Orthopedics[52]	2017	6	N/A	N/A	N/A	3
Sabbour[53]	2017	6	N/A	N/A	N/A	1
Goel[54]	2020	6	N/A	N/A	N/A	2
Crickard[58]	2004	7	N/A	N/A	N/A	3
Dreger[9]	2017	7	N/A	N/A	N/A	3
MarshallKloene.com[11]	2012	8	N/A	N/A	N/A	3

[a]Design: 1 = Retrospective Observational, 2 = scientific paper (no outcomes recorded), 3 = textbook, 4 = eBook, 5 = educational web-page, 6 = video, 7 = online presentation, 8 = independent website.
[b]Indication for TFA in observational studies; 1 = peripheral vascular disease, 2 = Chronic Infection/Ulceration, 3 = trauma, 4 = malignancy, 5 = other, NS = not specified.
[c]Closure technique described; 1 = fascial closure (no distal muscle stabilisation), 2 = myoplasty, 3 = myodesis, 4 = other.

Table II. Technique and recognized benefits/risks of myodesis

Resource	Patient position[b]	Muscles involved[c]	Drill hole location[d]	No. of drill holes	Benefits[e]	Complications[a]
Hsu et al.[5]	1, 2, 3	1, 2, 3	2	2	1, 4	1
Gottschalk et al.[13]	1, 2, 3	1, 2, 3	1, 1, 4, 4	4	2	ND
Putz et al.[30]	ND	1, 2, 3	1, 5, 6	ND	0	ND
Konduru et al.[12]	1	1, 2, 3	2, 3	2	1, 3	ND
Gottschalk et al.[28]	1, 2, 3	1, 2, 3	1, 4, 4, 6	2–5	1, 3, 5	ND
Geertzen et al.[6]	ND	ND	1, 4, 5, 6	4	2, 3	0
Jacobs et al.[31]	ND	1, 2, 3, 4	ND	ND	ND	ND
Anderson[32]	ND	1, 2, 3, 4	ND	ND	ND	ND
Ranz et al.[29]	ND	1, 2	1, 2, 4, 5	ND	2, 3	ND
Zolper et al.[7]	ND	1, 2, 3	ND	ND	2, 3	ND
Ertl et al. (2018)[33]	ND	ND	ND	ND	ND	ND
Tintle et al. (2014)[8]	ND	1	ND	ND	2, 3, 4	1
Pinzur et al.[36]	1, 2, 3	1, 2, 3	4	ND	1, 2, 3, 4	ND
Tintle et al.[37]	ND	1, 2, 3	ND	ND	1, 2, 3, 4	ND
Chadwick et al.[18]	ND	1, 2, 3, 4	ND	2–6	ND	ND
Kalapatapu[34]	ND	1	2	ND	2	ND
Eidt et al.[40]	2	1, 2, 3	1, 2, 3	6	1, 2	ND
Court-Brown et al.[42]	ND	1	ND	ND	1, 2, 3	ND
Wilson et al.[44]	ND	1	4	ND	1, 3	ND
Galland et al.[14]	ND	ND	ND	1	ND	ND
Wiesel et al.[15]	1, 4, 5	1	ND	ND	1, 2	ND
Yao et al.[16]	ND	1, 2, 3	ND	ND	1, 2	ND
Gottschalk et al.[17]	ND	1	ND	ND	1, 2, 3, 4, 5	ND
Feezor et al.[46]	ND	1, 2, 3	4, 5, 6	ND	2, 3	ND
Eidt et al.[47]	ND	1	2	ND	1	ND
Beard et al.[48]	3	ND	ND	ND	ND	ND
Smith et al.[4]	1, 2, 3	1, 2, 3	1, 4, 6	4–5	2, 4	ND
Sugarbaker et al. (2001)[49]	4, 5	1, 2, 3	ND	ND	ND	ND
Myers[1]	1, 2, 3	1, 2, 3	4, 6	ND	1	ND
Wheeless et al.[56]	ND	1, 3	ND	ND	1	ND
Berke et al.[10]	ND	1	ND	ND	5	1
Orthobullets[57]	1	1, 2, 3	ND	ND	ND	ND
Physiopedia Contributors[55]	ND	1, 2, 3	ND	ND	ND	ND
Dreger[9]	ND	1, 2, 3	ND	ND	ND	1
Crickard[58]	ND	1, 2, 3	4, 6	ND	ND	ND
Husky Orthopedics[52]	ND	1, 2, 3	1, 2, 4	4	1	ND
MarshallKloene.com[11]	ND	1	ND	ND	5	1

ND, no data; 0, other.
[a]Documented complications; 1 = myodesis failure.
[b]Patient positioning; 1 = elevation of ipsilateral hip, 2 = femur in extension, 3 = femur adducted, 4 = limb abducted, 5 = limb flexed.
[c]Muscles involved; 1 = adductor muscle, 2 = hamstring, 3 = quadriceps, 4 = hip abductors.
[d]Location of drill holes; 1 = anterior, 2 = anterolateral, 3 = anteromedial, 4 = lateral, 5 = medial, 6 = posterior.
[e]Documented benefits; 1 = maintains limb alignment, 2 = maximizes muscle function, 3 = improves ambulation, 4 = good soft tissue padding over distal femur, 5 = prevention of ‘‘adductor roll’’.

four[1,4,5,7,9,12,13,16–18,28–32,36,37,40,49,52,55–58] described additional attachment of the quadriceps and/or hamstrings, either by additional myodesis to the femur or suturing them to or over the muscular complex.

Drill holes. Securing the adductors (and/or other muscle) to the femur was almost always described by drilling femoral holes, through which sutures were passed. The number of drill holes ranged from 1 to 6[4–6,12–14,18,28,40,52] with a mode of 4.

Seventeen resources specified the location of drill holes.[1,4–6,12,13,28–30,34,36,40,44,46,47,52,58] All except one[30] stated at least one should be made on the lateral and/or antero-lateral aspects of the femur. Additional drill holes were placed

Table III. Technique and recognized benefits/risks of myoplasty

Resource	Patient positioning[a]	Muscles involved[b]	Documented recognized benefits of myoplasty[c]	Documented recognized complications of myoplasty[d]
Geertzen et al.[6]	ND	1, 2, 3	ND	ND
Ranz et al.[29]	ND	1, 2	ND	ND
Pinzur et al.[36]	ND	1, 2	ND	ND
Chadwick et al.[18]	ND	1, 2, 3, 4	ND	1
Ertl[35]	1	1, 2, 3, 4	ND	ND
Lumley et al.[39]	ND	1, 2, 3, 4	1	ND
Wilson et al.[44]	ND	1, 2, 3, 4	1	ND
Lamont et al.[45]	ND	2, 3	2	ND
Beard et al.[48]	3	2, 3	ND	1
Smith et al.[4]	1	ND	ND	1
Goel[54]	ND	2, 3	ND	ND

ND, no data; 0, other.
[a]Patient positioning; 1 = elevation of ipsilateral hip, 2 = femur in extension, 3 = femur in adduction, 4 = limb abducted, 5 = limb flexed.
[b]Muscles involved; 1 = adductor muscle, 2 = hamstring, 3 = quadriceps, 4 = hip abductors.
[c]Documented benefits; 1 = maximizes muscle function, 2 = good soft tissue padding over distal femur.
[d]Documented complications; 1 = creation of muscular sling.

anteriorly,[4,6,13,28–30,40,52] medially,[6,29,30,46] antero-medially,[12,40] or posteriorly.[1,4,6,28,30,46,58] Five resources suggested drilling tunnel hole/s (e.g., a drill hole made anteriorly that extends through the posterior cortex) through the distal femur.[8,13,14,30,40]

Muscle insertion. Most commonly, the adductor was secured to the lateral or antero-lateral aspect of the femur, often described as the ''Gottschalk method.''[4,5,13,28,34,36,37,40,44,46–48,52,58] Conversely, 3 resources described options for medial[12,29,30] or anterior adductor insertion.[29] After adductor myodesis, some resources described additional myodesis of the quadriceps,[1,4,13,16,28,36,40,46,56,58] hamstrings,[12,29,37,52,55] or both[7,9,18,30–32,46] to the femur. Three[18,31,32] suggested that the abductors should also be myodesed. Where specified, the quadriceps were attached to a posterior drill hole.[1,4,28,46,56,58] All but one[56] suggested that when additional myodesis of the quadriceps was undertaken, the hamstrings should then be sutured to the muscle complex. Alternatively, the hamstrings and quadriceps were sutured together over the end of the adductor-femoral complex,[55,57] or both sutured to the myodesed adductor.[5,40,49,56]

Suture technique and material. Suture type described included nonabsorbable,[1,8,13,28,32,34,40,47] slowly absorbable,[13,28,48] or braided polyester sutures.[8,32,47] Others suggested Dacron tape[49] or FiberTape and Knotless anchors.[5] Where reported, suture techniques involved loop mattress sutures[32] and Krackow locking sutures.[5,52]

Myoplasty. Distal muscle stabilization by myoplasty, involving the suturing of opposing muscle groups together over the femoral stump with no direct fixation to the femur, was described in 11 resources[4,6,18,29,35,36,39,44,45,48,54] (Table III).

Muscles involved. Four resources described myoplasty of the quadriceps to the hamstrings and the adductor muscles to the abductors.[18,35,39,44] Where specified, the adductors are sutured to the abductors first, followed by securing the quadriceps to the hamstrings.[35,39] Four resources described myoplasty only of the quadriceps to the hamstrings over the distal end of the femur.[36,45,48,54] One paper described suturing the adductor to the vastus lateralis and the remaining quadriceps to the hamstrings,[6] and one described the myoplasty of the adductor muscles to the hamstrings.[29] Few resources described suture technique or material; one resource described the use of interrupted mattress sutures to attach the adductors and abductors[39] and one described the use of PDS sutures.[48]

Recognized Benefits and Complications of Muscle Stabilization Techniques

This section summarizes the purported benefits and complications of distal muscle stabilization techniques described in resources which did not include patient outcomes.

Benefits. Documented benefits of myodesis included maintenance of femoral alignment,[1,5,12,15,17,36,37,40,42,44,47,52,56] preservation of muscle function,[4,13,15,29,34,36,37,39,40,44,46] and improved postoperative ambulation.[8,12,29,36,37,42,44,46] Two resources[39,44] suggested that myoplasty can also preserve contractile function of the muscles. One study[29] suggested myodesis stabilization may provide a larger hip adduction moment and therefore improved muscle balance. Six resources[4,5,8,36,37,45] suggested that myodesis or myoplasty provides a good soft-tissue covering over the femoral end.

Three resources[10,11,17] suggested myodesis acts to prevent the formation of the ''adductor roll'' (an accumulation of tissue on the anteromedial thigh above the socket line, which can cause significant discomfort). One paper suggested the preserved tension after myodesis limits the shear forces and movement of the skin interface, therefore optimizes conditions for wound healing.[13]

Complications. Complications were reported separately for myodesis and myoplasty, due to their different techniques. Myodesis failure, or loss of muscle fixation, was the main recognized potential complication of myodesis, described in 5 resources.[5,8–11] It may occur spontaneously;[10] however, it can also be secondary to inadequate bony preparation,[5] suture failure via drifting,[11] or knot loosening.[5]

The most commonly described complication of myoplasty was the formation of a ''muscular sling'', described in 7 resources.[4,13,14,16–18,48] Without anchoring of the muscles to the bone, the femur is mobile within the residual limb, which can lead to the muscle slipping off the bone[14] resulting in bursa formation[4,13,17] or ulceration of the bone through the skin.[18]

Outcomes

Eight studies (302 TFAs) reported patient outcomes after distal muscle stabilization. Seven studies (298 TFAs) primarily studied amputation with myodesis,[5,7,8,12,28,30,33] and 1 study (4 TFAs) included 2 TFAs with myodesis and 2 with myoplasty.[6] Indications for amputation varied (Table I). Reported outcomes were heterogenous and included operative time, complications, wound healing, revision surgery, and rehabilitation outcomes.

Operative procedure. Three studies[5–7] highlighted that the operative time was longer when undertaking a myodesis, although only 1 study[7] quantified this as an average of 90 min additional time in theater.

Early complications. Four studies[8,12,28,33] (237 TFAs, all myodesis) reported wound healing outcomes, with early wound complications noted in 17% ($N = 40$), including postoperative infection 14% (33 TFAs), sterile wound dehiscence 2.5% (6 TFAs), and prolonged wound leakage 0.5% (9 TFAs).

Late complications. Neuroma incidence[8,12,33] was 4.1% ($N = 9$), of which 7 (3.2%) required revision surgery. Two studies[5,28] (28 TFAs) reported 7% ($N = 2$) of amputees experienced pain on mobilizing; however, both patients remained fully active. One study[28] (20 TFAs) reported no patients developed the ''adductor roll''. Symptomatic heterotopic ossification was reported in studies with amputations secondary to trauma,[8,33] with a pooled incidence of 27.6% ($N = 50$), of which all underwent excision.

Myodesis failure was reported in 1 study (115 TFAs)[8] with a rate of 9.5%, of which all required reoperation.

Limb alignment and rehabilitation. Prosthetic use and postoperative ambulation were documented in 4 studies[5,12,28,30] (73 patients, 74 TFAs), with follow-up ranging from 12 weeks to 5 years. All of these patients (aged 21–89 years) had myodesis performed, with amputations secondary to a variety of indications. Fifty four patients (74%) were fitted with prosthetics. Three studies[12,28,30] (46 patients) reported further follow-up after initial prosthetic fitting with 93% (43 patients) still ambulating.

Postoperative muscle strength was measured in 2 studies.[12,28] One[28] (20 TFAs) reported improved muscle strength in those undergoing myodesis compared to those who had TFA with no distal muscle stabilization; however, no raw data were given. Another[12] assessed muscle power of the residual limb after myodesis, recording 6 of the 34 residual limbs had 4/5 muscle power in the adductors, while all others maintained 5/5 power in all muscle groups.

A study assessing magnetic resonance imaging data of 4 patients (2 of whom underwent myodesis and 2 myoplasty) measured intermuscular fat ratios.[6] Results demonstrated there was less intermuscular fat in the myodesed muscle, which was hypothesized to result in better motor function.

Two studies[5,28] (28 TFA) documented neutral femoral alignment was maintained in 100% of patients who underwent myodesis. One[28] reported that patients had a reduced incidence (no specific figures provided) of the ''lurching'' gait after myodesis.

One study[7] assessed mortality within patients who had undergone an amputation with a ''function-based approach''. Within their patients who underwent TFA with myodesis (41 patients), the 5-year mortality was 44%.

DISCUSSION

This is the first systematic review to report techniques for distal muscle stabilization in TFA and patient outcomes. Certain technical details, such as the use of the adductor musculature and the use of at least one femoral drill hole, were consistently reported, although the exact muscle selection (including the quadriceps and hamstrings), location of femoral attachment, and number of drill holes were heterogenous. Eight studies documented patient outcomes in relation to distal muscle stabilization techniques; however, most studies had a significant risk of bias. Limb alignment and prosthetic rehabilitation data were generally encouraging for distal muscle stabilization, but other outcomes were poorly reported, and there were no data comparing outcomes between TFA with distal muscle stabilization and TFA without distal muscle stabilization.

Distal Muscle Stabilization Technique

A surgeon's selection of amputation technique is often secondary to their personal training alongside expert opinions from medical textbooks.[6] Within the resources, including scientific papers, textbooks, and supplementary materials, the most commonly described technique for distal muscle stabilization is myodesis. However, in the authors' experience, this procedure is infrequently performed, suggesting training is a current issue.

The most prevalent technique described was myodesis of the adductors to a lateral or anterolateral drill hole. However, other insertions were suggested to adapt the procedure when available muscle length is compromised.[12,30] Ranz et al.,[29] using a simulated model, suggested changes in the adductor wrap position did not significantly alter the adduction moment arm during gait. However, they did demonstrate the muscle tension applied impacted muscle capacity, with higher percentages of preserved tension resulting in larger fiber forces. However, overtensioning should be avoided,[5] which is why it is suggested that myodesis be performed with the limb in extension and adduction, raising the ipsilateral hip. There was little consensus regarding the number and location of drill holes; one study[12] suggested using only 2 drill holes may reduce the risk of fracture in the presence of bone fragility, alternatively 3 resources[34,35,47] described stabilization by securing the muscle to the periosteum, forgoing the need for drill holes.

Advantages and Disadvantages

The adductor muscles are attached distally to the femur in comparison with the more proximal hip abductors. When standing, the agonistic-antagonist action of these muscle groups maintains the normal anatomical alignment of the femoral shaft axis at[9] degrees from the vertical.[28] During a TFA, the adductor muscle insertion is lost, whereas the abductor muscles are typically spared, leading to relatively unopposed abduction. It has been suggested that when the distal third of the femur is removed, 70% of the adductor mechanism may be lost.[13,15,17] Therefore, TFA without distal muscle stabilization commonly results in an abduction-flexion deformity. Patients overcome the resulting flexion-abduction deformity by resorting to a ''lurching'' gait (to balance the center of gravity, there is compensatory bending or rotation of the pelvis, trunk, thorax, and upper extremity[59]), which significantly increases energy expenditure during ambulation.[12]By re-creating the bony attachment of the adductors, myodesis provides a residual limb with a more neutral alignment,[5,28] providing a biomechanical advantage to aid in prosthetic use.

While resources have suggested that myoplasty may act to preserve contractile function,[39,44] clinical evaluation,[12] isokinetic testing, and radiological assessment of intermuscular fat ratios[6] suggest that myodesis also maintains muscle function and power. Jaegers et al.[60] presented evidence that re-anchored adductor muscles maintain ''almost normal'' activity. Therefore, myodesis can result in a more functional limb for ambulation.

Outcome measures regarding other complications within the cohort studies were heterogenous. Where reported, early wound complications were seen in 17%, suggesting wound healing rates are equivalent to TFA without distal muscle stabilization. However, in the absence of comparison with those who underwent no distal muscle stabilization and due to the confounding bias regarding the indication for TFA, it is difficult to reliably synthesize these data.

Despite the benefits of myodesis, loss of fixation or myodesis failure, although uncommon, is an important complication to consider. If it is not possible to preserve the tendon for myodesis, the muscle may be used. However, muscle tissues do not hold sutures well, and therefore ''drifting'' of the sutures down the muscle and even complete dehiscence can occur postoperatively.[10,11] Rupture of detachment of the myodesis can cause pain, ulceration, and uncontrolled falls.[61] Depending on ambulation status, this may be managed conservatively, but many result in need for reoperation.

Myodesis Versus Myoplasty

Although both techniques were described to provide a good soft-tissue envelope over the end of the femur,[4,5,8,36,37,45] the formation of a ''muscular sling'' after myoplasty was commonly reported.[4,13,14,16–18,48] Without direct muscle fixation to the bone, this technique relies on the physiological formation of scar tissue to fully stabilize the muscles to the bone.[4] If this is unsuccessful, the musculature may slide back and forth over the bony end which may lead to the formation of bursa and significant discomfort to the patient, or even ulceration of the bone through the skin requiring further surgery. It was suggested that this can be prevented by employing myodesis.[14,16,17,48]

Indications and Contraindications

While certain resources have suggested myodesis be attempted in all patients undergoing TFA,[4,5,13] relative contraindications included distal soft-tissue loss due to myonecrosis or trauma, malignancy requiring excision of the muscles or tendons, poor vascular supply, and poor bone quality. However, the heterogenicity of techniques demonstrates the adaptability of myodesis.

Peripheral vascular disease is considered by some contraindication for distal muscle stabilization,[32] due to poor tissue quality,[4,5,18,42,48] the risk associated with an increased operative time,[5–7] and increased susceptibility to infection.[6] However, there is currently no good clinical evidence to support this.[37] Others[12] have suggested the relative importance of distal muscle stabilization in the elderly dysvascular population. Many of the elderly dysvascular population have preexisting comorbidities which result in a low cardio-pulmonary reserve and subsequently may not be able to tolerate the increased energy demand of ambulation after TFA without distal muscle stabilization. As a result, these patients often do not get fitted with prosthesis. It is unknown whether distal muscle stabilization provides biomechanical advantages for sitting or transferring in patients who do not undergo prosthetic fitting. Gottschalk[13] highlighted that the adductor muscles receive its arterial supply from the obturator artery, which often remains patent in peripheral arterial disease; therefore, the muscle has a higher likelihood of being viable compared to other thigh musculature. Given this, it is important to recognize that reconstructive goals vary between patients. Factors such as indication for amputation, tissue viability, and preoperative physiological and psychological status should all be evaluated, and surgical technique should be adapted to accommodate the individual.

Limitations of Gray Literature

To ensure comprehensive review of surgical techniques for TFA, this review incorporated a diverse range of data sources, such as books, webpages, and videos, within the gray literature search. However, it is important to acknowledge the drawbacks associated with using such sources due to unknown and uncontrollable search algorithms. Furthermore, while textbooks do undergo a peer review process, webpages and videos do not go through the same rigorous evaluation, introducing potential concerns regarding reduced reliability and bias. Moreover, it is important to consider limitations regarding applicability, as books and webpages may not be updated regularly, and reproducibility since the library search was confined solely within Wales National Health Service library, and content found on webpages and videos can potentially be removed from the internet at any time.

CONCLUSION

Distal muscle stabilization, particularly adductor myodesis, is a commonly described technique for TFA, although operative technique is heterogenous. There is a significant paucity of outcome data, with no studies comparing it to closures without distal muscle stabilization. However, the outcomes suggest wound healing rates are equivalent to TFA without distal muscle stabilization, while demonstrating improvement to patients' rehabilitation potential with prosthetic limbs. Further research is needed to assess the benefits and complications of distal muscle stabilization in TFA.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.avsg.2023.07.105.

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