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REVIEW ARTICLE

Intermuscular force transmission along myofascial chains: a systematic review

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Abstract

The present review aims to provide a systematic overview on tensile transmission along myofascial chains based on anatomical dissection studies and *in vivo* experiments. Evidence for the existence of myofascial chains is growing, and the capability of force transmission via myofascial chains has been hypothesized. However, there is still a lack of evidence concerning the functional significance and capability for force transfer. A systematic literature research was conducted using MEDLINE (Pubmed), ScienceDirect and Google Scholar. Studied myofascial chains encompassed the superficial backline (SBL), the back functional line (BFL) and the front functional line (FFL). Peer-reviewed human dissection studies as well as *in vivo* experiments reporting intermuscular tension transfer between the constituents of a myofascial chain were included. To assess methodic quality, two independent investigators rated studies by means of validated assessment tools (QUACS and PEDro Scale). The literature research identified 1022 articles. Nine studies (moderate to excellent methodological quality) were included. Concerning the SBL and the BFL, there is moderate evidence for force transfer at all three transitions (based on six studies), and one of two transitions (three studies). One study yields moderate evidence for a slight, but not significant force transfer at one transition in the FFL. The findings of the present study indicate that tension can be transferred between some of the examined adjacent structures. Force transfer might have an impact in overuse conditions as well as on sports performance. However, different methods of force application and measurement hinder the comparability of results. Considering anatomical variations in the degree of continuity and histological differences of the linking structures is crucial for interpretation. Future studies should focus on the *in vivo* function of myofascial continuity during isolated active or passive tissue tensioning.

Key words: anatomy trains; fascia; myofascial continuity; tension transfer.

Introduction

Fascia is a mechanically active tissue with proprioceptive and nociceptive functions (Yahia et al. 1992; Schleip et al. 2005; Stecco et al. 2006, 2007, 2008, 2013b; Bhattacharya et al. 2010; Tesarz et al. 2011). In contrast to prior assumptions, it builds an extensive tensegrity network linking the skeletal muscles of the human body (Myers, 1997a,b, 2014; Wilke et al. 2016). This bodywide myofascial continuity holds particular significance because fascial tissues are able to change their tensional state. The presence of contractile cells has been demonstrated for the crural fascia (Staubesand & Li, 1996), the thoracolumbar fascia (TLF; Schleip et al. 2005) and the pectoral fascia (Stecco et al. 2008). Based on calculations, several authors suggest that the amount of force created by these cells is sufficient to influence musculoskeletal dynamics (Schleip et al. 2005; Willard et al. 2012). Although the existence of myofibroblasts represents a plausible explanation for stiffness changes, it most likely is not the only cause. In a recent experiment, Schleip and colleagues found that the lumbar fascia modifies its tensional state also in the absence of cellular contraction (Schleip et al. 2012a). In parallel to the stiffness change, an analogue alteration of the water content was observed. The authors therefore conclude that hydration might be the driving factor influencing fascial tension. Another theory proposes that muscle contraction directly stretches the overlying fascia, thereby altering connective tissue stiffness (Findley et al. 2015).

Regardless of the underlying mechanisms, the capability of fascia to modify its mechanical properties has potential implications for therapy and training. If tension can be

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increased and decreased in response to individual movement characteristics, it might be transmitted to neighbouring structures. Recent studies have demonstrated this for antagonistic and synergistic muscles (Maas et al. 2001; Huijing et al. 2003, 2007, 2011; Bojsen-Moller et al. 2010; Yucesoy, 2010). However, the direction of load transfer in these trials was lateral. In a systematic review, Wilke et al. (2016) showed that there is good evidence for the existence of three myofascial chains proposed by Myers (1997a,b, 2014): the superficial backline (SBL: plantar fascia, gastrocnemius, hamstrings, erector spinae); the back functional line (BFL: latissimus dorsi, contralateral glutueus maximus, vastus lateralis); and the front functional line (FFL: adductor longus, contralateral rectus abdominis, pectoralis major). Therefore, the aim of the present study was to provide a systematic overview on longitudinal in-series muscular force transmission along myofascial chains based on cadaveric studies and *in vivo* experiments.

Materials and methods

The systematic review was conducted adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Liberati et al. 2009; Moher et al. 2009) and the recommendations of Wager & Wiffen (2011) for ethical publishing of systematic reviews.

A systematic literature research was conducted between May 2013 and May 2014 by two independent investigators (FK, JW). Relevant articles were identified using Medline (Pubmed), ScienceDirect and Google Scholar (each 1900–2014). Studies focusing on force transmission through direct myofascial connections between the components of the following myofascial chains were targeted: SBL, BFL and FFL. Inclusion criteria consisted of: (i) study type anatomical dissection study or *in vivo* experimental study; (ii) load or force transfer via myofascial continuity as one/main outcome parameter; (iii) studied myofascial connection as part of the investigated myofascial chain; and (iv) publication in a peer-review-journal. Studies of other types (e.g. case reports, model-based calculations or animal studies) were excluded. The same applied to articles in languages other than German and English.

Search algorithms for the respective databases are listed in Table 1. The approach for Google Scholar was the same as in a previous systematic review (Wilke et al. 2016). Additionally, reference lists of all detected studies were checked. Data extraction was carried out by two independent investigators (FK, JW).

Table 1 Literature search algorithms for the respective databases

Database	Search term
MEDLINE (PubMed)	(“cadaver”[Mesh]) AND (“Fascia”[Mesh]) OR ((myofascial OR aponeurotic OR fascial) AND ((load OR tension OR strain) AND transfer))
ScienceDirect	(cadaver) AND ((“load transfer”) OR (“tension transfer”) OR (“strain transfer”))

To evaluate study quality, two researchers independently rated the included dissection studies by means of the QUACS scale. It has been shown to be a reliable and valid tool to appraise the quality of observational cadaveric studies, and has been described elsewhere in detail (Wilke et al. 2015). Methodological quality of *in vivo* experimental studies was evaluated with the PEDro scale (Sherrington et al. 2000). Levels of evidence were classified as strong (consistent findings among multiple high-quality studies), moderate (consistent findings among multiple low-quality studies and/or one high-quality study), limited (one low-quality study), conflicting (inconsistent findings among multiple studies), or no evidence (no studies available) according to the recommendations of the Cochrane Collaboration Back Review Group (van Tulder et al. 2003).

Results

The initial literature research yielded 1022 publications. After removing duplicates and irrelevant papers as well as applying exclusion criteria, nine studies (Vleeming et al. 1989, 1995; van Wingerden et al. 1993; Carlson et al. 2000; Barker et al. 2004; Erdemir et al. 2004; Carvalhais et al. 2013; Norton-Old et al. 2013; Cruz-Montecinos et al. 2015) were included (Fig. 1). Study quality was moderate to excellent (Tables 2 and 3). Detailed information about the methodological approach for each enclosed study is available from Table 4, the main findings for each examined station of the included myofascial chains are summarized in Table 5.

SBL

Two studies reporting force transfer between the plantar fascia and the Achilles tendon were found (moderate evidence). One trial identified force transfer between pelvic motion/hamstring movement and gastrocnemius muscle (moderate evidence), and three studies demonstrated force transfer between the hamstrings and the sacrotuberous ligament or the TLF, respectively (moderate evidence).

BFL

No study stating force transfer between the gluteus maximus and the vastus lateralis was found (no evidence). In contrast, three studies reported force transfer between the latissimus dorsi and the contralateral gluteus maximus, respectively, the TLF (moderate evidence).

FFL

One study reported transmission of force between the adductor longus and the contralateral distal rectus sheath, which turned out to be non-significant when compared with baseline values (moderate evidence). No study examining tension transfer between the rectus abdominis and the pectoralis major muscle was detected.

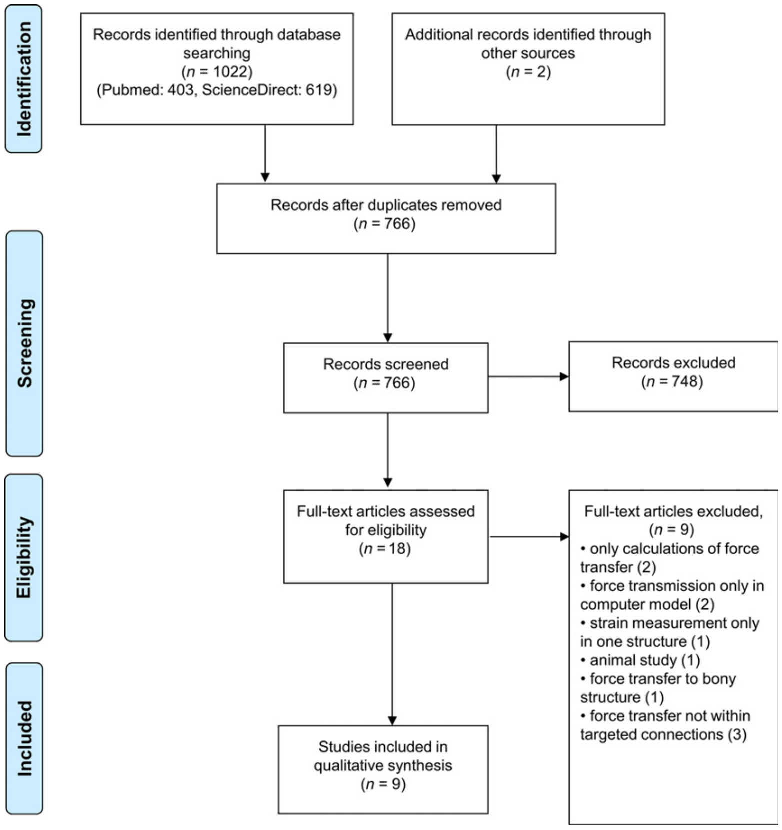

Fig. 1 PRISMA flowchart displaying the literature research.

Discussion

While evidence for the existence of morphological continuity between the skeletal muscles is growing (Stecco et al. 2009, 2013a,c), there is still a lack of research concerning the practical relevance of these connections. For the three myofascial chains that had been evidenced previously (Wilke et al. 2016) and were subject of this study, only nine studies reporting tension transfer between adjacent structures could be identified. This, however, is not unexpected, as recent histological and anatomical findings have changed the view of the biomechanical function of fascial tissues (van der Wal, 2009). To the authors' knowledge, the present review is the first systematic approach to evaluate tension transfer along myofascial intermuscular connections.

The current research shows that tension can be transferred between at least some of the examined adjacent muscles, which challenges the traditional view that muscles function as independent actuators during physiological movements (Herbert et al. 2008; Maas & Sandercock, 2008; van der Wal, 2009). The possibility of load transfer between muscles encourages targeting entire myofascial chains in the evaluation process, therapy and exercise. Instead of focusing on single structures, muscles or joints, more holistic diagnostic and treatment approaches seem appropriate for overuse conditions or radiation pain symptoms that involve several structures of myofascial chain. However, three factors hamper the applicability of the current results to *in vivo* conditions.

First, there was considerable variation in the amount of force transfer. This might be explained by discrepancies concerning the tissue type and the degree of morphological continuity. For the transition from plantar fascia to the Achilles tendon, both included studies that conclude that considerable force is transferred.(Carlson et al. 2000; Erdemir et al. 2004) In contrast to this, force transfer between adductor longus and rectus abdominis was only marginal despite structural continuity (Norton-Old et al. 2013). Though broad definitions of fascia (encompassing tendinous, aponeurotic and ligamentous tissue as well as the muscle fascia itself) emphasizing histological similarity have been proposed (Schleip et al. 2012b), different tissue types might explain the variance in transmitted force. Tissue hydration (Schleip et al. 2012a) as well as temperature (Sapin-de Brosses et al. 2010) have been shown to alter tissue stiffness, and could contribute to the observed variance in force transfer. *In vivo*, mechanical stimulation as well as TGF-β1 expression have been shown to alter myofibroblast activity (Hinz et al. 2001; Tomasek et al. 2002), which could in turn influence tissue stiffness and load transfer.

Second, the assessed outcomes and methods vary considerably between studies and examined body regions. Con-

Table 2 Methodological quality rated by the QUACS scale of the included dissection studies

	Study purpose	Sample data	Method of dissection	Condition of specimens	Education of investigator	More observers	Results precise	Statistics appropriate	Consistency of findings	Photographs included	Findings in context	Clinical relevance	Limitations addressed	Total score (%)
Barker et al. 2004;	✓	✓	✓	✓	–	–	–	✓	✓	✓	✓	✓	✓	77
Carlson et al. 2000;	✓	–	–	–	–	–	✓	✓	n/a	✓	✓	✓	–	58
Erdemir et al. 2004;	✓	✓	✓	–	–	–	✓	✓	n/a	✓	✓	✓	✓	75
Norton-Old et al. 2013;	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	✓	✓	85
van Wingerden et al. 1993;	✓	✓	✓	–	–	–	✓	✓	✓	✓	✓	✓	–	69
Vleeming et al. 1989;	–	–	✓	–	–	–	✓	n/a	✓	–	✓	✓	–	42
Vleeming et al. 1995	✓	✓	–	–	–	–	✓	n/a	–	–	✓	✓	–	42

n/a, not applicable.

Table 3 Methodological quality rated by the PEDro scale of the included *in vivo* studies

	Eligibility criteria	Random allocation	Concealed allocation	Groups similar at baseline	Blinding of subjects	Blinding of observers	Blinding of assessors	Measures from at least 85%	All subjects included	Statistic comparison	Point measures and variance	Total score
Carvalhais et al. 2013;	✓	✓	–	✓	–	–	–	✓	✓	✓	✓	6/11
Cruz-Montecinos et al. 2015	✓	n/a	n/a	n/a	n/a	–	–	✓	✓	✓	✓	5/8

n/a, not applicable.

Table 4 Methodological characteristics of included studies

Study	Study type	Sample size	♂	♀	Age (± SD/range)	Methods of force application	Methods of transmitted force measurement	Methodological quality
Barker et al. 2004	Cadaveric dissection	8	2	6	83 (73–101)	Calibrated force manually applied in 1 N intervals parallel to muscle fascicle orientation	Strain gauge, fascial displacement (photographs), fascial area affected (photographs)	'substantial' (77%)
Carlson et al. 2000	Cadaveric dissection	8	ns	ns	60–76	Tension mechanically applied to Achilles tendon up to 500 N at varying MP joint angles (0 °, 15 °, 30 °, 45 °)	Strain-gauge extensometer	'moderate' (58%)
Carvalhais et al. 2013	*In vivo* experimental study	37	15	22	24.92 (3.21)	Passive and active LD tensioning	Passive stiffness recorded by isokinetic dynamometer, resting joint position	'good' (6/10)
Cruz-Montecinos et al. 2015	*In vivo* experimental study	17	17	0	22.76 (1.8)	Translation of STL and hamstrings induced by pelvic motion	Ultrasonographic measurement of deep fascial displacement	'good' (5/8)
Erdemir et al. 2004	Cadaveric dissection	7	4	3	68.4 (22.5)	Special device for gait simulation, linear actuators pulling on AT	Fibre-optic strain measurement	'substantial' (75%)
Norton-Old et al. 2013	Cadaveric dissection	10	5	5	84 (75–98)	Forces of 20 N and 50 N applied by a mechanical winch to the muscle according to its line of action	Foil-type microstrain gauge	'excellent' (85%)
van Wingerden et al. 1993	Cadaveric dissection	6	2	4	70–90	Forces from 10 to 100 N applied with weights during simulated erect and flexed stance	Custom-made buckle-transducer	'moderate' (69%)
Vleeming et al. 1995	Cadaveric dissection	10	6	4	65–90	Traction of 50 N mechanically applied in the direction of muscle fibres	Estimation of traction effect by means of fascial displacement (photographs)	'moderate' (42%)
Vleeming et al. 1989	Cadaveric dissection	12	ns	ns	ns	Forces not exceeding 50 N applied to the muscle in the direction of the insertion	Visual inspection	'moderate' (42%)

AT, Achilles tendon; LD, latissimus dorsi; MP, metatarsophalangeal; ns, not stated; STL, sacrotuberous ligament.

Table 5 Main findings for each examined station of the included myofascial chains

	Transition	No. of studies	Main findings
SBL	Plantar fascia–Achilles tendon	2	Carlson et al. 2000: tension transferred from AT to PF in all tested cases, greater force transmission at greater MP joint angles; 100 N applied to AT resulted in mean forces from 116 to 256 N, 500 N resulted in mean PF forces from 314 to 511 N (MP angle between 0 and 45 °) Erdemir et al. 2004: force applied to AT and force measured at PF well correlated ($r = 0.76$; $P < 0.001$); linear regression: almost 50% of AT force could be measured in the PF during simulated walking
	Gastrocnemius–hamstrings	1	Cruz-Montecinos et al. 2015: pelvic motion induced displacement of the MG deep fascia, indicating strain transfer between STL/hamstrings and gastrocnemius
	Biceps femoris–sacrotuberous ligament	3	van Wingerden et al. 1993: Force transfer from BF to STL between 7 and 69%; high inter-individual variance and significant differences between specimen with partially or fully fixed STL to ischial tuberosity; if only partially fixed, also the lateral deep part of the ligament continuous with the BF tendon, and significantly more force was transferred; no differences in erected vs. flexed stance Vleeming et al. 1995: traction on BF led to displacement of deep lamina of the TLF; no direct measurement of force transfer Vleeming et al. 1989: tension on STL greatest for traction on GM and BF (if fused); STL and BF fused in only 50%; no direct measurement of force transfer
BFL	Latissimus dorsi–contralateral gluteus maximus	3	Barker et al. 2004: traction to LD and GM led to displacements at the TLF; traction to LD resulted in bilateral displacement and in greatest area of fascial displacement (Th12 to S1); traction to GM led to fascial displacement in posterior layer of TLF between L3 and S3, bilateral displacement varied between subjects; force of 10 N applied to LD or GM in direction of attaching muscles fascicles resulted in tensile force at L3 of 4.9/0.8 N in the posterior layer of TLF Carvalhais et al. 2013: passive LD tensioning led to lateral shift of hip joint resting position; active LD tensioning led to lateral sift of hip joint resting position and increased passive hip stiffness Vleeming et al. 1995: slight displacement of the superficial lamina of TLF when tensioning cranial fibres of LD; displacement homolaterally and to some extend contralaterally at L4-S2 when tractioning caudal fibres of LD; tractioning GM led to smaller homolateral, but greater contralateral displacement to LD traction conditions
	Gluteus maximus–vastus lateralis	–	No data available
FFL	Adductor longus–contralateral rectus abdominis	1	Norton-Old et al. 2013: force of 50 N applied to the AL resulted in a deformation in the contralateral rectus sheath between -0.64 and 1.11% compared to baseline length (mean: $0.23 \pm 0.43\%$; $P = 0.176$); high inter-individual variance of transferred strain
	Rectus abdominis–pectoralis major	–	No data available

AL, adductor longus; AT, Achilles tendon; BF, biceps femoris; BFL, back functional line; FFL, front functional line; GM, gluteus maximus; LD, latissimus dorsi; MG, medial gastrocnemius; MP, metatarsophalangeal; PF, plantar fascia; SBL, superficial backline; STL, sacrotuberous ligament; TLF, thoracolumbar fascia.

cerning the cadaveric studies, the type of force application differs widely between trials. The used methods range between mechanically applied forces (van Wingerden et al. 1993; Carlson et al. 2000; Barker et al. 2004; Norton-Old et al. 2013), simulated gait with a special device (Erdemir et al. 2004), to manual traction with either little (Vleeming et al. 1995) or no description of applied force (Vleeming et al. 1989). Even more important, also methods of transmitted force or strain measurement vary extensively between the included studies. While some authors use sophisticated methods like electronic strain gauges (Carlson et al. 2000; Barker et al. 2004; Norton-Old et al. 2013) or fibre-optic force measurements (Erdemir et al. 2004), others report tension transfer based on visual inspection (Vleeming et al. 1989). Others use photographs and report fascial displacement of the affected fascial area as an outcome measure (Vleeming et al. 1995; Barker et al. 2004). The different measurement devices and outcome parameters limit comparability of the results. Interestingly, measurements of tensile force and fascial areas of displacement showed similar trends, but did not correlate significantly in one study (Barker et al. 2004). It seems as if the various outcome parameters do not necessarily represent the same physical or biomechanical tissue properties.

The third factor relates to the use of cadaver specimen for biomechanical testing. Fixation in formalin has been shown to increase cross-linking in collagenous tissue (Chapman et al. 1990; Abe et al. 2003) and alter hyaluronic acid content (Lin et al. 1997), freezing and thawing of tendon specimen significantly changes their modulus (Clavert et al. 2001), all leading to altered biomechanical properties. Further, the architecture of muscular tissue concerning fibre bundle length and fibre pennation angle differ between cadaveric and *in vivo* measurements (Martin et al. 2001). In addition, the application of traction, even if applied in the fascicle direction, does most likely not adequately mimic muscular contraction. This raises the question to which extend the biomechanical behaviour of externally induced forces on formalin-fixed or thawed cadaver specimens can be transferred to the *in vivo* behaviour of human connective and muscle tissue.

Despite these factors, the current results have several implications for clinical practice. Contracture of the gastrocnemius muscle or tightness of the Achilles tendon are associated with plantar fasciitis and heel pain (Goff & Crawford, 2011; Pascual Huerta, 2014; Solan et al. 2014). Tension transfer from a stiff gastrocnemius–Achilles tendon complex to the plantar fascia is a feasible explanation for these overuse conditions, which is supported by the current findings. The results consequently endorse stretching of the Achilles tendon in the treatment of plantar fasciitis and heel pain (Roxas, 2005; Healey & Chen, 2010; Patel & DiGiovanni, 2011; Garrett & Neibert, 2013). Also, with reference to the FFL, strength imbalances between adductor longus and lower abdominal muscles are associated with groin pain in athletes (Fricker et al. 1991; Anderson et al. 2001; Morales-Conde et al. 2010; Choi et al. 2011). As in the one included study focusing on tension transfer between both muscles (Norton-Old et al. 2013), tension was transferred in most of the examined specimens. Improving the strength of the abdominal muscles while releasing tension of the adductors seems to represent a promising treatment for patients with groin pain. Finally, regarding the impact on sport performance, force transfer via myofascial chains might influence strength development and range of motion (ROM) in multisegmental movements as well as during locomotion. Despite some methodological flaws, recent studies have yielded encouraging evidence that previous *in vitro* findings can be transferred to *in vivo* conditions. For example, ankle ROM seems to be affected by forward head posture (Hyong & Kim, 2012), passive hamstring stretching tended to increase cervical spine ROM (Hyong & Kang, 2013), self-myofascial release on the plantar fascia increased sit-and-reach performance (Grieve et al. 2015), and ankle ROM seems to be affected not only by knee, but also hip position (Mitchell et al. 2008). These findings endorse incorporating entire myofascial chains in the strength and conditioning process and during flexibility training. Nonetheless, future studies should further investigate the *in vivo* tension transfer between adjacent myofascial structures or muscle groups.

Conclusion

The present systematic review points towards the fact that tension can be transferred between at least some of the investigated adjacent myofascial structures. However, the heterogeneity in methods of force application as well as the variety of outcome parameters used in the included studies hamper the comparability of the results. Considering anatomical variations in continuity as well as histological differences in the linking structures is crucial when interpreting results. Dissection studies and experiments should preferably be carried out in fresh cadavers, as fixation as well as freezing and thawing have been shown to alter biomechanical properties. In particular, future studies on the *in vivo* behaviour of adjacent structures should further investigate the practical relevance of the proposed intermuscular myofascial connections for exercise, prevention and rehabilitation.

Author contributions

Frieder Krause: concept and design, acquisition of data, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript and approval of the article. Jan Wilke: concept and design, acquisition of data, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript and approval of the article. Lutz Vogt: concept and design, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript and approval of the article. Winfried Banzer: concept and design, data analysis/interpretation, drafting of the manuscript, critical revision of the manuscript and approval of the article.

Conflict of interest

The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article, so they have no conflict of interest to declare.

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