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REVIEW

Evolving concepts in ventral hernia repair and physical therapy: prehabilitation, rehabilitation, and analogies to tendon reconstruction

J. E. Perez[1] · M. A. Schmidt[2] · A. Narvaez[1] · L. K. Welsh[1] · R. Diaz[1] · M. Castro[1] · K. Ansari[3] · R. W. Cason[3] · J. A. Bilezikian[4] · W. Hope[5] · A. D. Guerron[1] · J. Yoo[1] · H. Levinson[3,6]

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Abstract

Purpose The abdominal wall and musculoskeletal tendons share many anatomic, physiologic, and functional characteristics. This review aims to highlight these similar characteristics and to present a rationale why the treatment principles of successful musculoskeletal tendon reconstruction, including principles of surgical technique and physical therapy, can be used in the treatment of complex abdominal wall reconstruction or ventral hernia repair.

Methods The MEDLINE/PubMed database was used to identify published literature relevant to the purpose of this review.

Conclusions There are several anatomical and functional similarities between the linea alba and musculoskeletal tendons. Because of this reason, many of the surgical principles for musculoskeletal tendon repair and ventral hernia repair overlap. Distribution of tension is the main driving principle for both procedures. Suture material and configuration are chosen to maximize tension distribution among the tissue edges, as seen in the standard of care multistrand repairs for musculoskeletal tendons, as well as in the small bites for laparotomy technique described in the STITCH trial.

Physical therapy is also one of the mainstays of tendon repair, but surprisingly, is not routine in ventral hernia repair. The evidence surrounding physical therapy prehabilitation and rehabilitation protocols in other disciplines is significant. This review challenges the fact that these protocols are not routinely implemented for ventral hernia repair, and presents the rationale and feasibility for the routine practice of physical therapy in ventral hernia repair.

Keywords Ventral hernia · Prehabilitation · Physical therapy · Abdominal wall reconstruction · Anatomy · Patient-reported outcomes

Juan Esteban Perez and Michael A. Schmidt have contributed equally to the article.

✉ H. Levinson
howard.levinson@duke.edu

1 Division of Metabolic and Weight Loss Surgery, Department of Surgery, Duke University, Durham, NC 27704, US

2 Department of Physical Therapy and Occupational Therapy, Duke University, Durham, NC 27710, US

3 Division of Plastic, Maxillofacial, and Oral Surgery, Duke University, Durham, NC 27710, US

4 Department of General Surgery, New Hanover Regional Medical Center, Wilmington, NC 28403, US

5 General Surgery Specialists, New Hanover Regional Medical Center, Wilmington, NC 28403, US

6 Director of Innovation and Entrepreneurship, Associate Professor of Plastic and Reconstructive Surgery, Pathology, Dermatology and Surgical Sciences, Departments of Dermatology, Pathology, and Surgery, Duke University Medical Center, DUMC 3181, Durham, NC 27710, US

Introduction

In 2006, there were more than 350,000 ventral hernia repairs (VHR) in the United States [1]. There is robust hernia literature on appropriate patient and mesh selection, how to perform surgeries, and how to optimize patients prior to surgery; however, interestingly, there are only a few articles on how to manage VHR patients post-operatively and even fewer articles discussing the role of physical therapy in the patient recovery. This gap in the literature is surprising given the fact that VHR is, in essence, a musculoskeletal reconstruction of the trunk, and physical therapy is known to play an important role in musculoskeletal rehabilitation. To better understand the role of physical therapy in VHR, this review article will highlight the similarities between abdominal wall and extremity musculoskeletal anatomy, similarities in the treatment of VHR and soft tissues of the extremity (including surgical techniques and devices used in repair), and, finally, the principles and techniques of physical therapy related to clinical care and enhanced patient-reported outcomes.

Anatomy and function: similarities between abdominal skeletal muscle and extremity skeletal muscle

The abdominal wall is a complex multilayered neuromuscular structure composed of right and left external/internal oblique muscles, transversus abdominis muscles, and rectus abdominis muscles enveloped in the investing fascia, where right and left fascia fuses in the midline to become the linea alba. Extending from the xyphoid process to the pubic symphysis, the linea alba is formed by the confluence of the oblique and transverse abdominal muscles. The linea alba is formed by both anterior and posterior rectus sheath fibers until the arcuate line (linea semilunaris of Douglas), in which there is no posterior component. Histologically, collagen fibers are found in three distinct orientations. The most superficial layer follows an oblique orientation, followed by a layer of transverse fibers and finally a second oblique layer of opposite orientation [2]. This complex structure of abdominal muscles and fascia originating from bone (spine, ribs, and pelvis) and fusing at the linea alba is akin to the anatomy of the pes anserinus tendon in the leg, formed by the fusion of semitendinosus, gracilis, and sartorius muscles, and the achilles tendon, formed by the fusion of gastrocnemius and soleus (Fig. 1). Hence, the linea alba can be thought of as the "central tendon" of the abdomen, which stabilizes right and left abdominal muscles to enable form and function. The similarity between abdominal wall fascia and tendons is so great that some authors have used abdominal wall fascia to repair achilles tendons [3]. Conversely, thigh-based fasciocutaneous flaps such as the tensor fascia lata flap and anterior lateral thigh flap are routinely used to reconstruct abdominal wall defects [4]. By drawing an analogy between abdominal wall fascia and tendons, it encourages us to think about applying principles and techniques in extremity tendon reconstruction to central abdominal tendon reconstruction (more commonly referred to as VHR).

Moreover, similar to extremity skeletal muscles where an unrepaired tenotomy (i.e., cutting a tendon) leads to muscular contractures, when the linea alba is unrepaired, imbalanced lateral forces from intra-abdominal pressure and unopposed oblique and transversus muscle contraction lead to oblique and transversus muscle retraction and muscle shortening [5]. This muscle shortening may lead to irreversible muscle contractures or reversible spasticity, which causes lateral rectus muscle displacement, hernia formation, and possibly back pain or pelvic dysfunction [6]. In certain instances, oblique and transversus muscle

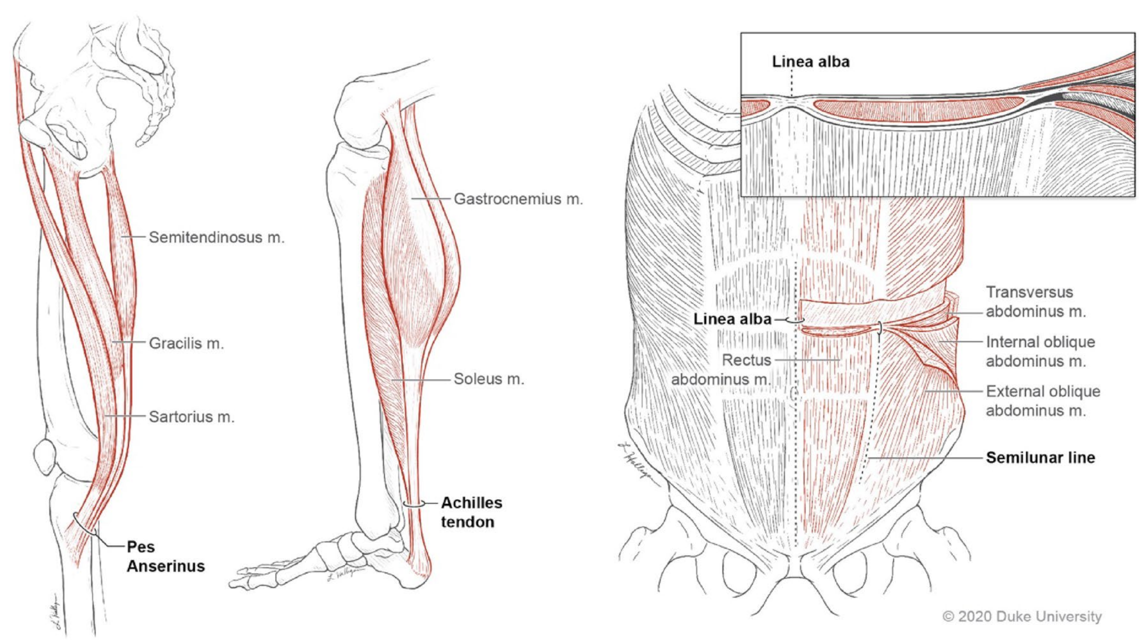

Fig. 1 Comparative anatomy of tendons that coalesce in the extremities and fascia that coalesces in the abdominal wall. In the upper leg, the semitendinosus, gracilis, and sartorius muscles fuse to form the pes anserinus, a central tendon inserting on the proximal tibia. In the lower leg, the soleus and gastrocnemius muscles fuse to form the Achilles tendon, a central tendon inserting on the dorsal aspect of the calcaneus. Similarly, the rectus abdominus, transversus abdominus, internal oblique, external oblique fascias fuse to form the linea alba, a "central tendon" in the medial aspect of the abdominal wall. Illustrated by Lauren Halligan, CMI, published with permission, Copyright Duke University 2020

retraction is reversible (e.g., a small gap exists between right and left rectus muscles) allowing the rectus muscles to be centralized in the midline during VHR, though a component separation or even botulinum toxin injections are often required to mechanically disrupt the lateral muscle pull or relax the oblique and transversus muscles, respectively. This is equivalent to extremity tendon lengthening procedures [7]. In other instances, oblique and transversus muscle retraction is irreversible (e.g., a large gap exists between right and left rectus muscles) and shortened muscles prevent the rectus muscles from being centralized in the midline during VHR despite the use of botulinum toxin and component separation. In these instances, the amount of tension required to bring together the wound edges would result in tissue ischemia and suture pull through. Interestingly, we cannot predict which patients will develop reversible versus irreversible lateral muscle retraction. When patients develop reversible retraction, the hernia is repaired and supported by a mesh bolster in either an onlay, retrorectus, or intraperitoneal orientation. This maintains rectus muscle position in the midline by distributing forces laterally and creating a scar plate. When rectus muscles cannot be centralized because of irreversible muscle changes, VHR requires spanning, bridging, or inlay mesh placement across the midline defect. Spanning VHRs are problematic in that the repairs are inferior to bolster mesh VHR and they are associated with both higher complication rates and higher hernia recurrence rates [8]. This leads us to believe that ventral hernias should be repaired as quickly as possible once they are diagnosed to prevent irreversible deformities, assuming that active infections have been treated and there are no additional contra-indications to surgery.

While there are no studies that describe the histologic changes of abdominal muscle retraction (i.e., spasticity versus contractures), it is reasonable to infer that abdominal skeletal muscle alterations are similar to extremity skeletal muscle contractures including changes in architectural, functional, and molecular structures [9, 10]. Contractures are associated with fewer sarcomeres along myofibrils, increased resistance to passive stretch, decreased muscle fiber length, shortening of muscle connective tissue, and increases in muscle stiffness [5, 11, 12]. Unloaded skeletal muscle undergoes changes in fiber type composition, decreased cross-sectional area, and pathologic fibrosis consistent with myopathic disuse atrophy [11]. Muscles with contractures have decreased extensibility and increased stiffness. Hence, ventral hernia repairs are in dire need of a method to prevent or overcome contractures. Not surprisingly, the treatment of contracted extremity skeletal muscles follows similar approaches to the treatment of contracted abdominal skeletal muscles (Table 1) with the premise in VHR being to reduce midline tension [5].

Table 1 Similarities in the management principles of extremity skeletal muscle and abdominal skeletal muscle contractures

Treatment	Extremity skeletal muscle	Abdominal Skeletal muscle
Physical therapy	X	X
Splinting	X	
Botulinum toxin	X	X
Surgical release or lengthening of the causative muscle/tendon unit	X	X
Postoperative splinting	X	
Surgical tendon transfer	X	
Application of bridging mesh		X
Application of autologous fascia through flap reconstruction		X

Key Point: Given that the abdominal wall and musculoskeletal tendons share multiple anatomic, physiologic, and pathologic features, it is reasonable to infer those same principles of repair and recovery can apply to tendon reconstruction and hernia repair.

Suture and mesh: principles of tendon reconstruction and relationship to laparotomy closure

Given the anatomic and functional similarities between the abdominal wall and extremities, it is no surprise that both tendon and abdominal wall reconstruction follow similar surgical principles. In tendon reconstruction, there is a large body of literature investigating various surgical techniques, including the selection of suture material, method of suture application, application of mesh, and the rationale behind perioperative decision making.

The ideal suture material for tendon repair should maintain its strength up to 6–8 weeks postoperatively, at which time the tendon repair regains sufficient strength to resist rupture [13]. However, there is no clear consensus regarding suture material for tendon repair. Non-absorbable, high-tensile strength materials such as braided polyethylene terephthalate or braided high-molecular-weight polyethylene are commonly used and have all been shown to provide enough strength to allow early mobilization [14]. The ideal suture material for laparotomy repair has also been extensively studied and a recent Cochrane systematic review and meta-analysis by Patel et al. [15] found that monofilament suture reduces the risk of incisional hernias more than multifilament suture. However, there were no differences when comparing the use of absorbable versus non-absorbable suture. Surprisingly, fast absorbable versus slow absorbable sutures performed equivalently, but perhaps rapid absorption may be unsafe given the fact that wounds require 3–6 months to regain 60–80% of their unwounded breaking strength. A meta-analysis by Henriksen et al. [16] reported conflicting results as it concluded that incisional hernia rates are significantly reduced when using slowly absorbable suture.

Perhaps, the most important predictor of successful tendon reconstruction and hernia repair is the redistribution of tensile stress across the injury. Strategically increasing stitch density, via the number of suture strands crossing the injury and/or bites extending away from the repair site, has been shown to improve force distribution and repair outcomes (Fig. 2) [14, 17]. In hand surgery, data suggest that techniques with approximately six strands of suture provide the strongest repair [14]. Experimental models have demonstrated that increasing the number of strands (2, 4, and 6 strands) increases the ultimate stress that the tendon can withstand (26.3 N, 41.6 N, and 75.08 N), respectively) [17]. The underlying principle is that tensile stress = force/area. Thus, by dividing the force across multiple strands and over a greater area (via multiple bites), the tensile stress on any single strand or bite is decreased, therefore reducing the likelihood of suture tearing through the repair or breaking and causing gap formation and tissue strangulation. Optimal stress distribution (i.e., tension-free repair) is thought to lead to fewer tendon rupture recurrences and ventral hernia recurrences. However, one must be careful to balance the amount of material present, as to not create an entire inflammatory body or strangulate the tissue.

To provide context to how tendon suture techniques are being applied to VHR today, consider the Israelsson 4:1 suture length:wound length repair, the small bites versus large bites for closure of abdominal midline incisions (STITCH) trial (Fig. 3), the recently invented mesh suture, and the T-line Hernia Mesh™ (Fig. 4), where surgeons report that increasing stitch density and distributing force over a broad surface area leads to fewer hernia recurrences [18–27]. Israelsson reported that using a suture that was four times the length of a laparotomy wound hernia recurrence rates were significantly decreased compared to shorter sutures. The reason why the longer suture was more effective than shorter suture was that the stitch density was increased and more densely placed sutures (Fig. 3b) resulted in better tension distribution and higher overall tensile strength [18–24]. Likewise, the STITCH trial; a prospective, multicenter, double-blind, randomized-controlled trial, which was based on the principles of Israelsson, found in a cohort of 545 patients that small bites (more densely spaced suture), (Fig. 3c) compared to large bites resulted in a 48% decrease in the incidence of incisional hernia [25].

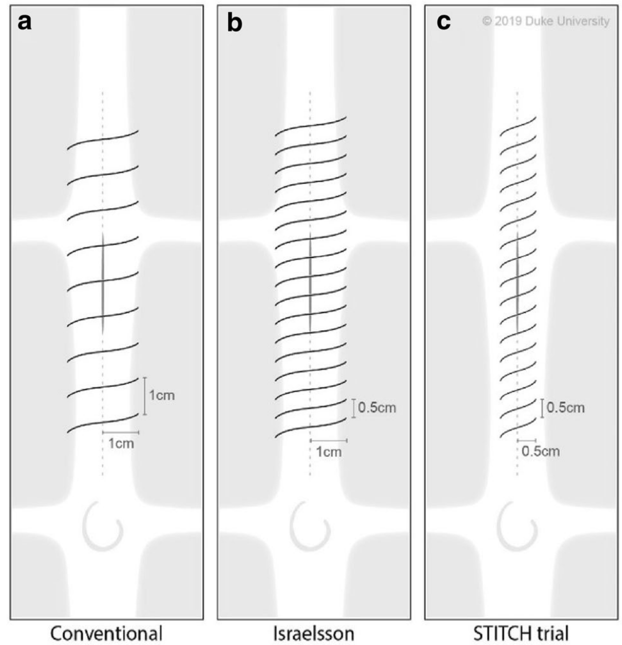

Fig. 3 Comparison of laparotomy closures. In a conventional approach, the closure suture pattern takes 1 cm bites with 1 cm travel. Israelsson's 4:1 wound length-to-suture length ratio increases the density of suture bites and strands crossing the injury. The STITCH trial found that smaller bites at higher densities further improve outcomes (as compared to larger bites). Illustrated by Lauren Halligan, CMI, published with permission, Copyright Duke University 2020

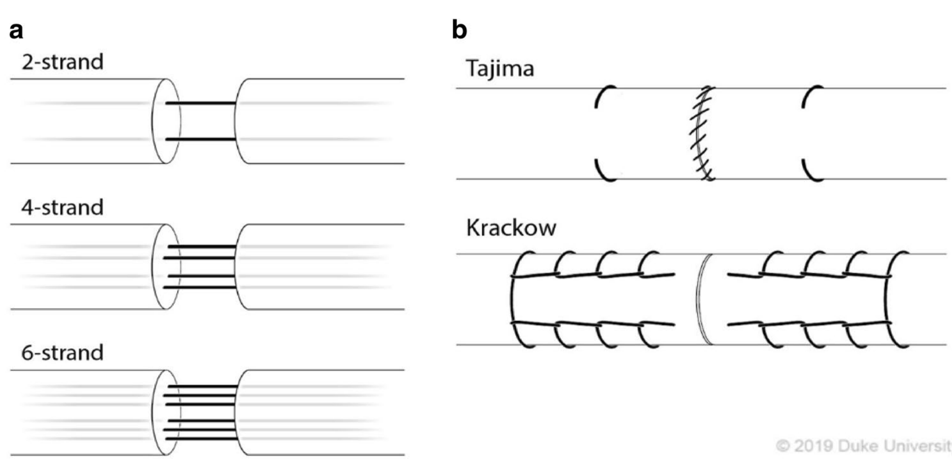

Fig. 2 Approaches to overcome tensile stress in tendon reconstruction. Increasing stitch density redistributes forces to increase the strength of the repair. **a** Multi-strand (2, 4, and 6) repair divides overall force across each strand. **b** Successive bites through the tissue divide forces and distribute tension away from the repair site, as demonstrated by the Tajima and Krackow techniques. Illustrated by Lauren Halligan, CMI, published with permission, Copyright Duke University 2020

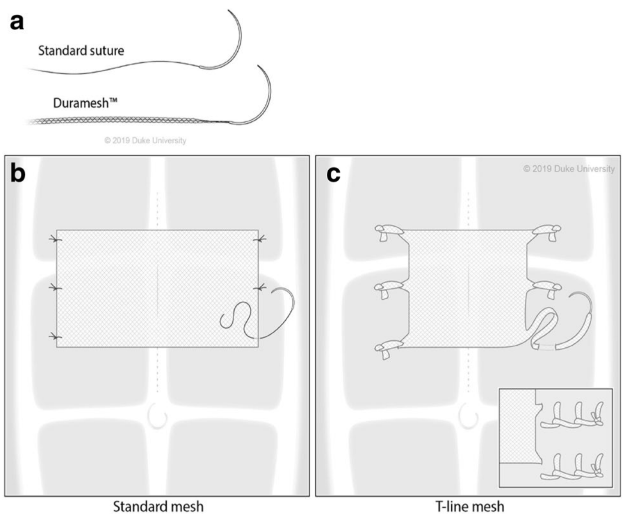

Fig. 4 Hernia repair techniques beyond standard suture. The mesh-like design of Mesh suture improves tensile strength. The application of mesh in addition to suture helps to increase the anchoring device surface area. T-line Hernia Mesh™ further distributes tensile stress through the seamless integration of the mesh body and sutures. Alternate suture patterns of the T-line extensions may further improve force distribution. Illustrated by Lauren Halligan, CMI, published with permission, Copyright Duke University 2020

Dumanian et al. took a slightly different approach to solve the problem of hernia recurrence and invented a mesh suture to distribute tensile stress (Fig. 4a) [26]. In animal studies, he reported mesh suture doubled the strength in early laparotomy repairs and tendon repairs, and the mesh suture was fully bioincorporated into the tissue by post-operative day eight where the fibrovascular ingrowth around the filaments added additional strength [28]. The filaments acted as a scar scaffold, with the increased surface area of the implant magnifying the foreign body reaction in comparison to a standard suture. Mesh suture has been used successfully in an unpublished clinical trial in Armenia (NCT 03,940,560) in orthopedic tendon surgery. In the United States, strips of mesh have been used as sutures to achieve abdominal wall closures in both clean and contaminated fields with good results [29, 30]. Similarly, Levinson et al. created the T-line Hernia Mesh™ to distribute tension and maintain tissue closure (Fig. 4c) by reducing tensile stress up to 275% with a novel mesh that has seamless integration of sutures in the mesh body [27, 31]. The mesh sutures are 15 × the width of #0 suture and are highly effective at anchoring mesh to tissue.

Another approach to increasing anchoring device surface area in soft-tissue repair is the application of mesh instead of suture alone [32]. In a landmark multicenter study published in 2000, Luijendijk et al. [33] found 3-year incisional hernia recurrence rates of 24% for patients treated with mesh and 43% for patients treated with suture. In a 10-year follow-up longitudinal study, the cumulative hernia recurrence rates were 32% for mesh repair and 63% for suture repair [34]. Given the clear benefits of mesh in treating ventral hernia, it is no wonder that surgeons have recently begun applying mesh to prevent ventral hernia occurrence at the time of laparotomy closure and this practice should continue to become widespread. There are now more than a dozen randomized clinical trials that illustrate the benefits of prophylactic mesh placement [35]. This robust clinical data are exactly why orthopedic surgeons also use mesh in complex knee extensor reconstruction and rotator cuff tendon reconstruction [36]. Without mesh, a healing wound only reaches ~ 80% of its original wound breaking strength [37]. In the field of hernia surgery, the question is not whether mesh should be applied at the time of laparotomy, but rather in which patients, by which surgeons, using which meshes, and by which techniques.

Key Point: Technical aspects of hernia repair and tendon reconstruction follow the same principle: a repair stronger than the forces applied with adequate tension distribution, by providing multiple points of contact between the repair material and tissues, minimizing the risk of gap formation or tearing.

Rehabilitation/physical therapy rationale

In tendon reconstruction, early functional rehabilitation is a mainstay of therapy and critical for good outcomes [38]. For example, early mobilization and weight-bearing significantly reduce Achilles tendon re-rupture rates, and the Duran and Kleinert rehabilitation protocols are ubiquitously applied to hand flexor tendon repairs within a week of surgery [39–41]. Likewise, rehabilitation in the first few months following VHR is likely paramount for preventing hernia recurrence, enhancing function, reducing pain through non-pharmacological management, improving patient well-being, and decreasing fatigue. All of these potential clinical improvements in a field that is just beginning to evolve [42].

Ericksen et al. [43] demonstrated in a group of 25 patients undergoing laparoscopic VHR that compared to their baseline, they had higher levels of pain (60/100 on VAS), decreased quality of life in the physical functioning, bodily pain, and physical component subscales along with increased physical fatigue for 1–6 months following surgery ($p < 0.05$). This demonstrates the need for physical therapy intervention in the early post-operative period to aid in the improvement of pain and physical function subscales. Pezeshk et al. [44] reported in a series of 275 patients that a structured rehabilitation program decreased VHR recurrence rates from 22 to 9% ($p < 0.01$) over 5 years. Of patients who developed a recurrence, recurrences were slower to occur in the rehabilitation group (13 months, $p < 0.05$) compared to the control group (6 months). Pre-operative assessment is the first step in considering physical therapy rehabilitation for VHR patients.

Key Point: Physical therapy protocols are fundamental in the recovery after musculoskeletal tendon reconstruction, improving outcomes, and minimizing re-rupture rates. Early experience with PT following VHR shows promise in reducing hernia recurrence rates, demonstrating the need for further studies.

Assessment: pre-operative physical therapy assessment of function and *health*

The initial physical therapy assessment of a VHR patient should include analysis of patient impairments which include: activity limitations, participation restrictions, body function/structure restriction, and analysis of contextual factors (including environmental and personal factors), in accordance with the International Classification of Functioning and Health (ICF) model (Fig. 5) [45]. Impairments can include physiological (i.e., trunk and extremities) or psychological system dysfunctions (i.e., fear of movement following surgery) that affect optimal recovery following surgery. Activity limitations include the execution of tasks by the patient such as completing activities of daily living or participating in recreational activities. Participation restrictions are the ability of the patient to be involved in life activities in a social context with others. Environmental factors comprise understanding the patient's physical, social, and attitudinal environment in which they live and conduct their lives. Assessment with the ICF model takes into account the entire patient's condition, extending beyond the VHR. The ICF model captures the overall health status of the patient along with identifying modifiable and non-modifiable factors that affect patient recovery, but it does not measure patient physical performance. Physical performance measures such as strength, endurance, and physical function are typically quantified with sophisticated measurement systems, not normally available in clinics. To overcome reliance on expensive infeasible machinery, Parker et al. [46] identified simple non-machine based objective measurements for abdominal wall strength testing in patients with VHR. They applied two clinical tests [trunk raising (TR) and double leg lowering (DLL)] in 45 patients and each test was scored on a scale of 1–5 with a cumulative 10-point overall abdominal wall strength score (Fig. 6). Lower scores indicated a weak abdominal wall and higher scores indicated full optimal strength. The median score was five points. Strength testing clustered around individuals with low abdominal strength (≤ 3 points) or high (≥ 7 points) abdominal strength. The tests were found to be reliable (DLL 0.96 and 0.87, TR 1.0 and 0.95), reproducible (correlation DLL 0.81 TR 0.81), and demonstrated significant agreement (93%) in quantifying abdominal wall strength. While further studies are warranted, this practical approach to abdominal wall strength testing in the clinic pre-operatively appears to be accurate and reliable for baseline assessment prior to surgery.

Key Point: Successful rehabilitation depends on establishing the patient's baseline (preoperative) functional status and identifying any barriers to a successful implementation of physical therapy protocols.

Assessment: patient-reported outcome assessments

In addition to the paucity of data related to physical performance testing, data are also lacking for VHR specific patient-reported outcome metrics. Fortunately, the broad outcome measurement tool; Patient-Reported Outcomes Measurement Instrument System® (PROMIS) may be

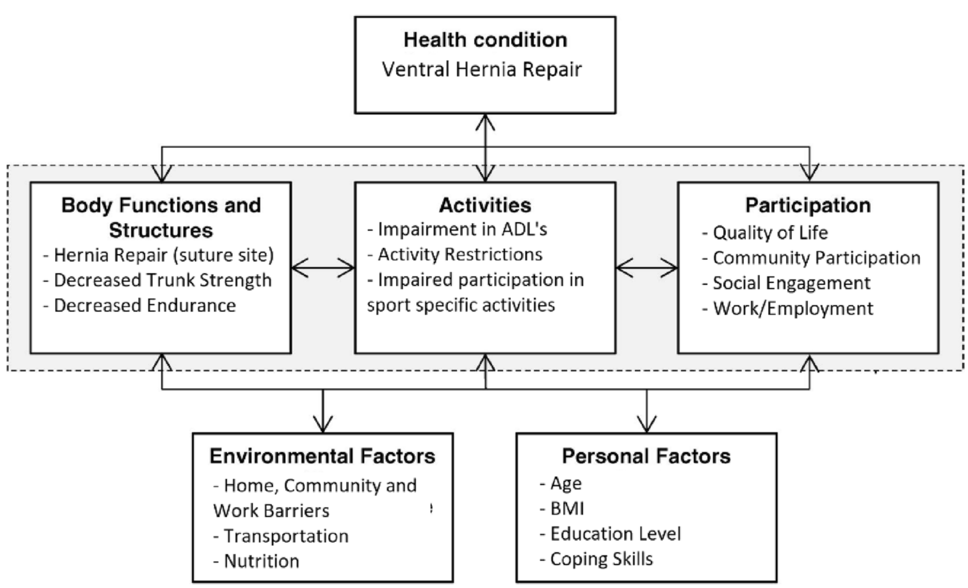

Fig. 5 International Classification of Functioning and Health (ICF) with example patient following ventral hernia repair. *ADL's* activities of daily living, *BMI* body mass index

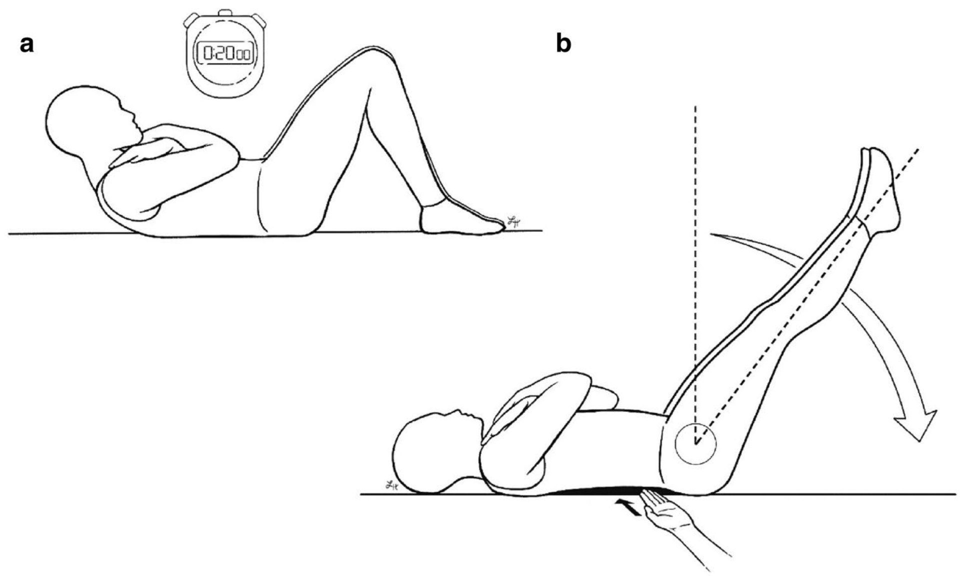

Fig. 6 Abdominal Wall Strength Testing. **a** Trunk raising test—a patient lifting with crossed arms and holding their shoulders off the table for 20 s demonstrates a score of 4/5 or good abdominal strength. **b** Double leg lowering test—a patient lowering their legs to an angle of 21–30 degrees from vertical before losing the ability to keep their back flat against the table (and examiner's hand) demonstrates a score of 3/5 or fair abdominal strength. Illustrated by Lauren Halligan, CMI, published with permission, Copyright Duke University 2020

sufficient for VHR patients. PROMIS is a flexible system tool designed to measure self-reported physical, mental and social health, and well-being [47]. In 2010, Cella et al. [47] calibrated 11-item banks of the PROMIS instrument on over 21,000 individuals demonstrating PROMIS to be reliable and a precise measure of generic symptoms and functional reports comparable to competing for legacy instruments. The PROMIS system contains fixed items encompassing seven domains including physical function, anxiety, depression, fatigue, sleep disturbance, ability to participate in social roles and activities, pain interferences, and pain intensity (10-point VAS scale). Each domain of the PROMIS tool is scored independently and the raw score for each domain converted to a standardized T-score for each participant within each domain. T-scores are classified based on the level of symptom and impairment severity as detailed in Table 2. PROMIS scores can be utilized in replace of disease-specific measures to compare outcomes to normative data and across large populations of patients. It also provides a universal language for comparing outcomes in surgical and non-surgical patients [48].

Key Point: The Patient-Reported Outcomes Measurement Instrument System (PROMIS) is a comprehensive functional status assessment tool that encompasses multiple functional domains, and standardizes outcome measures for comparison purposes.

Table 2 Example interpretation of PROMIS scores

		Symptoms/impairments (T-score)		
Domain	Within normal limits	Mild	Moderate	Severe
Physical function	≥ 55	40–54	30–39	≤ 29
Anxiety	≤ 54	55–59	60–69	≥ 70
Depression	≤ 54	55–59	60–69	≥ 70
Fatigue	≤ 54	55–59	60–69	≥ 70
Sleep disturbance	≤ 54	55–59	60–69	≥ 70
Ability to participate in social roles and activities	≥ 55	40–54	30–39	≤ 29
Pain interference	≤ 50	50–54	55–64	≥ 65

*Patient-Reported Outcomes Measurement Instrument System® (PROMIS). Measurement includes seven subscales and normative data for interpretation to indicate patients within normal limits or mild, moderate, or severe symptom impairments

Treatment: physical therapy functional prehabilitation

While it is not clear that prehabilitation would be beneficial for all surgical patients, the concept has been gaining momentum across surgical disciplines because of benefits in clinical care and quality of life outcomes [49]. A recent systematic review and meta-analysis demonstrated prehabilitation improved aerobic capacity and decreased operative complications in test subjects compared to controls. The review also demonstrated prehabilitation reduced post-operative pain, lessened anxiety, decreased hospital length of stay, and improved overall physical function [49]. In 2018, Barberan-Garcia et al. [50] investigated the use of a personalized intensive prehabilitation program on major abdominal surgery. They randomly assigned 71 patients to standard care and 73 patients to a structured 6-week prehabilitation program. Prehabilitation encompassed motivational interviewing, high-intensity endurance training, and promotion of physical activity. Primary outcomes included the proportion of patients suffering from post-operative complications and secondary outcomes included endurance time during cycle ergometer testing. The intervention group demonstrated significantly fewer post-operative complications ($p < 0.001$) and enhanced aerobic capacity (135 min) compared to the standard of care group [50].

Key Point: Pre-operative functional prehabilitation programs have proven to be effective in reducing complications in a diverse array of surgical disciplines, including major abdominal surgery.

Treatment: physical therapy post-operative rehabilitation

Development of individualized tailored physical therapy programs for post-operative recovery requires careful consideration of several key factors including frequency of participation, exercise intensity, length of training, type of training (aerobic vs anaerobic), and progression of program [51]. Unfortunately, there are a few studies on the proper progression of physical activity following VHR, but there is ample scientific literature for rehabilitation following extremity reconstruction that could be related to VHR [52–54]. Anterior cruciate ligament reconstruction is one of the most well-studied areas in post-operative rehabilitation and offers insights into proper phasing of recovery. Adams et al. [55] highlighted five phases of post-operative recovery including immediate, early, intermediate, late, and transitional. He described Phase 1 (immediate) as including protection of the surgical site, range of motion, and muscle initiation initially after surgery; Phase 2 (early/intermediate) including muscular endurance of surrounding abdominal wall musculature; Phase 3 (early/intermediate) including muscular strength of the abdominal wall including extremities; Phase 4 (late/transitional) including the muscular power/speed/agility phase with return to activity-specific training; and Phase 5 including the transitional period into an independent program with a focus on long-term health maintenance. Other surgical procedures including hip arthroscopy and rotator cuff repair share a similar framework for phased rehabilitation based on tissue healing [53, 56]. While a widely adopted physical therapy protocol following VHR does not yet exist, the ideal program adopted in the future will be consistent with these existing tendon/ligament rehabilitation guidelines.

The post-operative program should take into consideration the patients' baseline physical activity and strength levels. Pre-operative assessment of ventral hernia patients with the previously describer testing (Fig. 6) can be helpful to gather baseline information on the patients' strength level to tailor the rehabilitation program accordingly (Table 3). The strength testing can assist in stratifying patients into low, medium, or high functional strength levels. These strength levels can help to formulate the level of intensity for the post-operative rehabilitation program. For example, a patient with a total strength score of three or less on strength testing would be classified in a low functional strength category. A lower intensity post-operative rehabilitation program for aerobic and anaerobic conditioning would be indicated (aerobic: walking 0.5 miles per day at 20 min/mile pace; anerobic: Strengthening exercises performed 10 repetitions for 2 sets). A patient with greater strength prior to surgery with a score of seven or greater would need a higher intensity program to match their functional abilities. High-intensity rehabilitation would incorporate more strenuous aerobic and anaerobic conditioning (aerobic: walking 2.0 miles per day at 12 min/mile pace; anerobic: Strengthening exercises performed 20 repetitions for 2–3 sets). Ideal post-operative rehabilitation programs match the patients' baseline abilities and stratifying patients based on this can be a helpful alternative to a one size fits all approach.

Table 3 Stratified rehabilitation program

Strength category	Total abdominal wall strength testing score	Rehabilitation program
Low	≤ 3	Low-intensity program
Medium	4–6	Medium-intensity program
High	≥ 7	High-intensity program

*Frequency, time, type, and intensity of exercises increase from Low to High

Key Point: The extensive literature surrounding rehabilitation in tendon reconstruction provides an ideal starting point to develop a structured VHR program. An ideal post-operative program should take into account the patients' baseline physical function.

Treatment: post-operative restrictions and activity guidelines

For post-operative recovery, activity guidelines and restrictions vary widely, because there is a paucity of evidence to support specific restrictions, such as wearing binders and limiting exercise [57]. Bouiver et al. [58] surveyed 50 surgeons in France regarding abdominal binders following laparotomy and found that a majority of surgeons (94%) utilize abdominal binders despite a lack of evidence indicating any benefit. Surgeons identified their use of binders as a habit learned during surgical training [59]. Christofferson et al. [60] randomized 56 patients undergoing laparoscopic hernia repairs and determined that binders did not affect clinical outcomes but improved patient comfort post-operatively. In contrast, the European Hernia Society offers no guidelines on the use of abdominal binders due to the lack of sufficient justification for their utility in post-operative complications [59].

In terms of activity restrictions, current recommendations are also lacking [59]. Guttormson et al. investigated the relationship between intra-abdominal pressure and physical activities commonly restricted following surgery in a group of five healthy control patients. The Valsalva maneuver and a forceful cough produced more intra-abdominal pressure (77.1 mm Hg and 112.3 mm Hg, respectively) than all tasks analyzed, including lifting 40 lb from the floor (69.8 mg Hg) [60]. However, the relevance of these numbers to hernia recurrence and outcomes is unknown. Another study randomized 95 women undergoing pelvic prolapse reconstruction to either liberal post-operative activity or restricted post-operative activity, where liberal activity was a resumption of normal post-operative activity at the patients' self-directed pace and restriction included avoiding heavy lifting or strenuous activity for 3 months postoperatively. Patients in the liberal restriction group were equally satisfied with surgical outcomes and reported fewer prolapse and urinary symptoms as the control restriction group, which suggests that liberal activity is safe and effective [61]. In terms of tendon reconstruction and rehabilitation, the history of Achilles tendon repair rehabilitation is instructive. Patients with Achilles tendon repairs were historically treated with immobilization with a restrictive foot/ankle brace to decrease complication rates and prevent re-tears [62]. However, the current evidence supports the contrary that early mobilization leads to significant improvements in outcomes such as early return to activity, increased range of motion, improved blood supply to the surgical site, and reduced muscle atrophy [63]. Hence, literature from abdominal wall studies, pelvic reconstruction, and tendon reconstruction suggest that early mobilization of patients following surgical repair leads to better outcomes and satisfaction. The extent and degree of activity require further investigation.

Key Point: Activity restriction and the use of abdominal binders are common practices following intra-abdominal surgery, despite a lack of evidence supporting these practices.

Physical therapy and pain management

Pain management strategies after VHR, including pharmacology and non-pharmacological approaches, are critically important for long-term success. In 2012, Liang et al. [64] determined that 25% of patients undergoing laparoscopic hernia repair reported poor quality outcomes due to poor cosmesis, hernia recurrence, or persistent debilitating pain. With the current opioid crisis, non-pharmacologic management in the post-operative period is garnering more attention. There are many different options for non-pharmacological management of pain, but the most significant reduction in pain reduction has been shown to occur with structured physical exercise programs including aerobic and resistance training along with cognitive behavioral therapy [65].

Structured physical exercise programs

Jones et al. [66] evaluated pain tolerance thresholds in 24 healthy (non-VHR) patients prior to and following a structured exercise program. The healthy participants were randomized to either a structured aerobic exercise-training regimen or a standard physical activity control group for 6 weeks. The structured aerobic activity group demonstrated significant increases in aerobic fitness ($t = -5.39$, $P = 0.004$, + 14.6%) compared to no significant change in the control group ($t = 1.45$, $P = 0.72$, −2.8%). Ischemic pain tolerance also demonstrated significant improvement in the intervention group ($t = -3.15$, $P = 0.036 + 20.3\%$) compared to no change in the controls ($t = 1.77$, $P = 0.44$, −3.7%). Öte Karaca et al. [67] evaluated the effects of aerobic exercise on patients with chronic musculoskeletal pain. Fifty patients were randomly assigned to either a control group that received 2 weeks of conventional physical therapy or an experimental group that received the 2 weeks of conventional physical therapy with an additional 30 min of aerobic exercise training. The authors concluded that both groups demonstrated a significant reduction in visual analog pain scores (intervention 26.3 ± 18.09 vs 22.5 ± 17.09 control, $P < 0.001$). The aerobic training group demonstrated significant improvements in pain threshold compared to the control group (-2.08 ± 4.06, $P = 0.623$ vs -0.12 ± 4.21, $P = 0.023$) and additionally demonstrated significant improvements in aerobic capacity (1.7 min, $P = < 0.001$ vs −0.7 min, $P = 0.001$). Other studies have seen similar results in the use of exercise training at high-intensity exercise levels for improvement in pain, disability, psychological strain, and depressive symptoms [68, 69].

Cognitive-behavioral therapy

Finally, cognitive-behavioral therapy (Table 4) including cognitive restructuring, graded exposure, activity scheduling, mindfulness practice, and pain coping skills has demonstrated effectiveness in decreasing pain and catastrophizing behavior [70, 71]. Van Koulil et al. [72] randomized 158 patients with fibromyalgia to two tailored cognitive-behavioral training programs in conjunction with a progressive exercise intervention compared to a waitlist control. They found that progressive exercise along with cognitive behavioral therapy reduced pain (2.3 point decrease, $P < 0.001$), fatigue (9.68 point decrease, $P < 0.001$), disability (3.15 point increase, $P < 0.001$), and anxiety (2.62 point decrease, $P < 0.001$). Similar findings have been demonstrated in chronic low back pain patients that are administered therapeutic exercise in conjunction with cognitive-behavioral

Table 4 Cognitive-behavioral therapy glossary

Term	Definition
Cognitive restructuring	Identifying irrational or maladaptive negative thoughts known as cognitive distortions
Graded exposure	Gradually exposing patients to activity that was once thought as being fearful or painful to perform
Activity scheduling	Specifically scheduling pleasant activities to address issues of social isolation or negative mood
Mindfulness practice	Mediation/relaxation-based techniques to help relax the body and mind to help reduce stress
Pain coping skills	Distraction based techniques to help draw the focus away from perseverating on pain

*Glossary of common terminology and definitions of interventions utilized in cognitive-behavioral therapy approaches

training compared to therapeutic exercise alone (–2.2 decrease in pain compared to control, $P<0.001$) [73]. Finally, Archer et al. [74] compared cognitive behavioral therapy delivered by physical therapists for 102 patients following lumbar spine surgery. The cognitive-behavioral training decreased patients' overall pain (–1.7 points, $P<0.05$) and disability (–17.3%, <0.05) while also improving general health (6.8 points, <0.05) and improved physical performance outcome scores (5-chair stands 4.3 s, $p=0.02$; TUG 1.8 s, $p=0.02$; 10 m walk 0.09 m/sec, $p=0.02$).

Key Point: Alternatives to opioids for the management of post-operative pain have become increasingly recognized, of which structured exercise programs, as well as cognitive behavioral therapy, have been shown to be particularly effective.

Conclusion/future work

The abdominal wall is a part of the musculoskeletal system with a "central tendon" and analogies may thus be drawn with extremity tendons in terms of anatomy, function, repair, and rehabilitation. Extremity tendons are usually treated by orthopedic and plastic surgeons and abdominal wall reconstructions are usually treated by general surgeons and plastic surgeons. The key implication of this review article is that abdominal wall reconstruction should be approached similarly to extremity tendon reconstruction.

Tension-free repair (i.e., not technically tension free, but rather distributed tension) is one of the most important principles in surgical technique. Multi-strand repairs, Tajima, and Krackow suturing techniques have repeatedly been shown to be superior in tendon repairs, and the Israelsson 4:1 wound length:suture length ratio and the STITCH trial provide general surgeons with the same objective approach in abdominal wall repair. Solutions to the problem of distributing tension have been proposed by improvements made in surgical tools of suture and mesh such as mesh suture and T-line Hernia Mesh™.

Physical therapy and early mobilization are concepts that are considered standard of care in extremity tendon repairs, but are absent among abdominal wall reconstruction protocols. The content of this article outlines both the necessity and feasibility of such a protocol to be put in place following such repairs. The implementation of prehabilitation protocols have the potential to shorten hospital length of stay, decrease pain, decrease opioid use, and improve patient quality of life and post-operative recovery protocols should provide the same benefits with the addition of reduced hernia recurrences.

Observation of recent trends demonstrate that improvements in perioperative care will likely be made by coordinated diverse care pathway teams, innovative new medical devices, and learning from colleagues in other medical and surgical disciplines. Future studies should follow the implementation of a structured perioperative physical therapy program for patients undergoing ventral hernia repair. Outcomes should include hernia recurrence and complication rates as well as quality of life (e.g., PROMIS scores and HerQLes surveys) measures.

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Compliance with ethical standards

Conflicts of interest Dr. Levinson is the Inventor/Founder, Chief Medical Officer of Deep Blue Medical Advances, the company that commercializes T-Line Mesh. In addition, Dr. Levinson has a patent licensed to Deep Blue Medical Advances. William Hope, MD has received consulting/research honorarium from CR Bard, speaker honorarium from WL Gore, consultant/speaker honorarium from Intuitive Surgery, and consultant honorarium from Medtronic. Jin Yoo, MD has received consultant/speaker honorarium from Alesi Surgical, Medtronic, and WL Gore, and speaker honorarium from ConMed. Alfredo D. Guerron, MD has received consultant honorarium from Levita and Biom'Up, speaker honorarium from WL Gore and Medtronic. The other authors declare that they have no conflict of interest.

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