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Review

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Biomechanical principles of a permanently durable abdominal wall reconstruction: current status and potential future development

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Abstract

The article reviews the biomechanical principles of durable abdominal wall reconstructions. The aim is to provide insights and conclusions for future research in this area. Incisional hernia repair implies the creation of a compound made of tissue, textile, and fixation elements. A pulse load bench test for incisional hernia repair has been available since 2014, and its influences are evaluated in three different versions of the test stand. Based on these evaluations, a biomechanical concept for long-term durable reconstructions was determined. To apply the concept to individual patients, computed tomography of the abdomen at rest and during the Valsalva maneuver was used. A load limit can be given for every patient based on the hernia defect area (CRIP- critical resistance to impacts related to pressure). By considering the mesh to defect area ratio, the retention strength of a planned reconstruction can be calculated (GRIP-gained resistance to impacts related to pressure). The gripping coefficients for tissues vary significantly, up to 18 fold. About half of the patients have overall tissue distensions up to 350% or more, with potential high regional variations. The surface retention forces for hernia meshes and for different sutures, tacks, and adhesives span a wide range of 14fold. Suturing a defect strengthens the reconstruction up to 3fold. Furthermore, recalculating data taken from multicentric randomized studies on primary sutures reveals that improved GRIP values are associated with reduced rates of incisional hernia. Repairing consecutive incisional hernias according to the GRIP concept results in no recurrence and low pain levels after one year. A future policy for market access of repair materials should include cyclic load bench testing. Moreover, a tailored approach to incisional hernia repair should take into account the biomechanical aspects involved.

Keywords: Hernia, incisional hernia, biomechanics, GRIP, biomechanically calculateed hernia repair, durable hernia repair, durable incisional hernia repair

INTRODUCTION

The recurrence rate of incisional hernia repair is 25% five years after mesh-based incisional hernia repair[1]. This rate has remained relatively constant over the decades, disregarding open, laparo-endoscopic, or robotic approaches[1]. A biomechanical concept gave excellent results in incisional hernia repair after one year[2,3]. The concept is based on the analysis of cyclic loads mimicking coughs or Valsalva maneuvers. Dynamic intermittent strain (DIS) is repeatedly delivered to assess compounds made from tissue, hernia mesh, and fixation materials. The analysis includes a self-built bench test and results in coefficients characterizing the adhesiveness of each component[4,5]. The results are summed in a critical (CRIP) and a gained resistance towards impacts related to pressure (GRIP).

So far, about 10% of commercially available hernia meshes, sutures, tacks, and adhesives are biomechanically characterized with pulse loads for clinical purposes[6,7]. The design of a future investigational strategy has to take into account a basic principle of pulse load testing for incisional hernia repair: the retention forces of the components are not simply additive but rather depend on factors such as the energy uptake of the tissues in their different lamina, the cut-out and fiber orientation, the specific configuration of various materials, and the impact area[8,9]. In order to concentrate on relevant topics, it is essential to define specific research questions. The potential for future advancements in this field includes areas such as policy making and regulatory and clinical approaches.

Historical perspective

In the field of material sciences, the durability of compounds is influenced by factors such as cyclic load, boundary conditions, interface influences, notch effects, stress concentration, and their regional distribution. Research investigating these influences has been ongoing since 1855[10,11]. Standardization of cyclic load testing for fatigue strength has been increasingly implemented since the establishment of DIN 50100 in 1951[12]. In 1958, trauma surgeons adopted this approach with a focus on biomechanics and cyclic load testing[13]. Despite a success story in bone and ligament surgery, testing is not yet fully standardized as compared to solid materials. The most recent version, DIN 50100.2022-12, describes load-controlled fatigue testing for metallic specimens and components. The first steps for polymeric and biological materials have recently started with an effort to adapt ASTM standards to musculoskeletal soft tissue[14]. Current research focuses on a standardized test specimen, the test coupon. In the realm of soft tissue surgery, a biomechanical “fail-safe” approach is just beginning to emerge. However, there is still no consensus regarding the standardization of the test coupon or of the boundary conditions.

Ten years ago, our groups of surgeons and basic scientists started cyclic loading as a test in order to improve the results of incisional hernia repair. A biomechanical approach was chosen. Applying cyclic pulse loads on a bench test (DIS), mesh materials were tested and classified, simulating coughing actions[6]. Using computed tomography of the abdomen at rest and during the Valsalva maneuver, the tissue elasticity of individual patients was assessed when necessary[2]. The CRIP and GRIP of the mesh-tissue interface were calculated[2-9]. The C/GRIP formula incorporates various aspects of the surgical techniques, such as suturing with a small-stitch-small-bite technique, tackers, or adhesive for enhanced bonding [Figure 1]. Here, we present research questions influential to durable incisional hernia closure. In our belief, a durable repair of the abdominal wall can be defined as GRIP > CRIP. Which boundary conditions derived from cyclic load

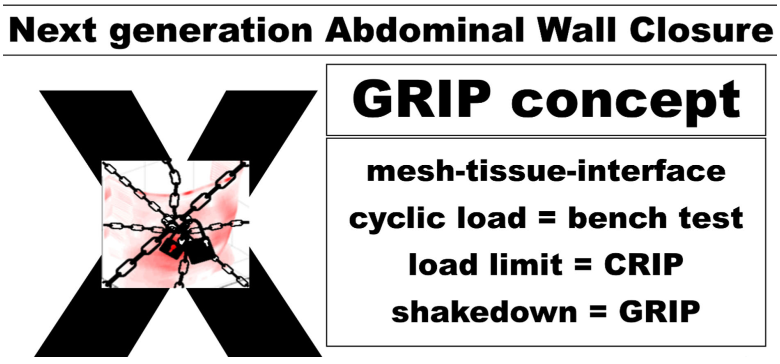

Figure 1. This is a figure representing the GRIP concept. Forces acting on the abdominal wall are considered as linked chains. Failure mainly occurs at the mesh-tissue interface. Cyclic load is delivered on a bench test and can assess the influence of the different forces. A load limit CRIP must be surpassed for a durable reconstruction. A shakedown process as a prerequisite for healing requires a sufficient GRIP of the reconstruction CRIP: critical resistance to impacts related to pressure; GRIP: gained resistance to impacts related to pressure.

testing in material sciences can be investigated and applied to the clinical situation in the future? What are the consequences for policy making and regulatory and clinical approaches?

STATE OF ART

Is cyclic load relevant for abdominal wall reconstruction?

Most daily activities imply cyclic load to the abdominal wall[15]. This is evident from the increase in intraabdominal pressure during these activities. Notably, water immersion decreases intraabdominal pressure and reduces pulse load to the abdominal wall[16]. However, increasing effort elevates intraabdominal pressure even during water immersion. During straining and vomiting, high values exceeding 250 mmHg are measured[17]. Intraabdominal pressure values above 120 mmHg start to destroy an abdominal wall reconstruction after 325 repetitions[18]. Such loads are easily reached hundreds of times every day in human life.

What kind of cyclic load needs to be studied?

The load spectrum starts with sharp peaks lasting only a few milliseconds, such as those experienced during coughing. Additionally, the spectrum includes increasing pressure levels over seconds once the glottis is closed, as seen during the Valsalva maneuver[19-22]. Both forms of load can be delivered with the cyclic load test stand available to date for incisional hernia repair. So far, plateau phases up to 400 msec have been investigated[2,5]. These plateau lengths are already reached after 30% of an isometric maximal lifting effort with longer plateaus at higher efforts[23].

Under which circumstances is a bench test load relevant to human daily life?

Both pulse and plateau loads were observed during walking, jumping, climbing stairs, vomiting, or straining for bowel motions. Among these activities, the highest intraabdominal pressures, usually above 200 mmHg, were found during squats[17,24]. In daily life, pressure levels reach these values at about 10% of the values per hour[15]. Within one hour, 76% of all measured values reach 100 mmHg, while an additional 13% exhibit peak values up to 200 mmHg. It is important to note that these data were derived from a few healthy volunteers, and large-scale measurements in patients are currently unavailable. By counting coughs in patients and assuming intraabdominal pressure peaks as previously reported, a load case of 400 and more peaks above 200 mmHg was taken as a critical load in one-third of our patients[4,20]. During prehabilitation, intraabdominal pressure peaks could be evaluated for individual patients suffering from incisional hernias. It should be noted that individuals with better physical fitness tend to have lower intraabdominal pressures at a given load, but they may experience more repetitions[20-22].

What are important boundary conditions?

A load-limit curve involves the number, magnitude, and duration of pressure elevations[18,25]. The resistance of reconstruction depends on the energy distribution between mesh, tissue, and fixation elements[5]. The elasticity of both tissue and mesh is critical for the regional energy distribution and the formation of areas of high tissue distorsion[5,18]. These areas, referred to as "hot spots", can initiate failure mechanisms such as creeping motion when the elastic-plastic deformation does not reach a shakedown state[5,26]. In the context of shakedown, it implies that plastic deformation is finally reached, after which loads are taken up and energy is dissipated in a purely elastic manner without further deformation. If further deformation occurs, the effect is called "ratchetting shakedown", leading to the failure of the reconstruction. This concept holds true for both primary closure and hernia repair[27]. To prevent slippage, it is crucial to enhance the energy distribution in these hotspots[28]. Additionally, careful attention should be given to notches and cracks during reconstruction, as these structural weaknesses can initiate failure[29,30].

Which factors determine the durability of an interface between tissue, mesh, and fixation material?

The gripping coefficients vary significantly, with tissues exhibiting an 18fold variation, hernia meshes showing a 14fold variation, and different sutures, tacks, and adhesives displaying a 14fold variation. Suturing a defect increases the retention force by up to 3fold. About half of the patients experience overall tissue distensions of up to 350% or more. Regional variation can be high. Recalculating data from multicentric randomized studies on primary sutures, incisional hernia rates drop with better GRIP values[2-8]. Due to the magnitude of the influences, a durable combination can be chosen from the variables mentioned above. From a physical perspective, this combination should permit shakedown within a given timeframe and volume at given elasticity, strain, and pressure levels[26]. For practical purposes, a toolkit of meshes and fixation elements should be at the disposition of the surgeon. In critical cases, computed tomography at rest and during the Valsalva maneuver can be used to assess individual tissue elasticity[2,17].

Can notch effects and stress concentration be assessed to strengthen weak spots?

Incisional hernia repair deals with defect cut-outs in multi-layered polymeric composite structures under multiaxial tensile loads[9,31,32]. Using the cyclic load bench test described above, round, rhomboid, and elliptical defects of the same sizes were closed with standardized sutures and tested for durability. After 425 DIS strains, no reconstruction held tight after round defect closure, whereas 30 and 100% were durable after suturing the other defect shapes. Recent work points to a change in stress distribution during loading conditions[33]. Concepts derived in material sciences from fracture mechanics, such as fracture toughness, elastic fracture mechanism, and stress concentration or intensity, can be applied to porcine muscle tissue and tendons. Tear resistance, buttonhole formation, suture slackening or fixation retention force, and other effects commonly observed in surgical practice are not fully explained by current theory and warrant further investigation[34,35]. Most likely, a better word than "fracture toughness" should be used in the surgical field to characterize the ability of a material to maintain strength despite the presence of a macroscopic crack. Since all work is based on tissue or mesh, "cyclic tear resistance" might be used. At least, tissue and mesh resistance or "toughness" should be distinguished. Using the existing cyclic load bench test, standardized suturing was successfully used to close round defects up to diameters of 7.5 cm durably[27]. Larger defects develop tears in the tissue lateral to the suture line, most probably due to local stress concentrations[36]. Mesh augmentation is successful as long as the stress concentration is considered[37]. This is an area where the scientific evaluation has just started. A cyclic load bench test augmented by tension assessment might be the next step to further improve incisional hernia repair.

How influential is the regional load distribution?

Soft tissue simulation has been successful for the computational planning of orthognathic and breast surgery[38,39]. The first attempts to evaluate the human abdominal wall have been published[40,41]. The anisotropic distribution of tissue elasticity in scarred battlefield abdomen poses a particular challenge. A regional load distribution can directly be derived from CT scans of the abdomen at rest and during the Valsalva maneuver[2,5,18]. The strain values derived from these analyses easily overburden the retention forces of most meshes[42]. An initial calculation of interfibrillar shear stress of collagenous tissue yields a value corresponding to 224 mmHg[29]. Newly formed collagen fibers are easily overloaded by such strain values[43,44]. Primary and recurrent incisional hernia develop early but become obvious late[1,45]. Suture slackening or fascial dehiscence up to 11 mm are obvious after four weeks already. 96% of the cases with slackened sutures develop an incisional hernia after 40 months. 96% of all incisional hernias, and the respective recurrences are obvious after ten years. The disregard for the regional load distribution generates small areas of overload. These are followed by button holes, lattice breakage, and mind-boggling loss of domain hernia orifices. Considering biomechanical approaches and taking regional load distributions into account permits the durable repair of both primary and recurrent incisional hernia repair[3].

Most important: how can a surgeon apply biomechanics to the clinical case?

An incisional hernia is a frequent consequence of major surgery, causing pain and disability. After repair, every third hernia recurs, with even worse results after each subsequent redo. In the United States, a cost of 7.5 billion $ is spent per year on incisional hernia repair. In Europe, similar figures have to be expected since yearly cost amounts in Germany alone to 1.8 billion €. Surgeons, patients, insurance companies, and policymakers eagerly seek options to lift this burden. Biomechanically stable repair of the abdominal wall reduces both pain and recurrence after one year, potentially saving most of these costs[1,2]. For the design of a GRIP-based durable hernia repair, retention coefficients of the repair materials are mandatory.

In a three-dimensional hernia repair in an abdominal wall, stress and strain effects are observed in all directions depending on the twist gradients occurring within the given load space. The deformation in solids, such as hernia meshes, follows the displacement gradient tensor and the deformation gradient tensor in every volume element within the material[14]. A consequence of these different gradients is local instabilities within the reconstruction at the interface of mesh and tissue.

Using cyclic loading in a bench test, such as DIS, described in this study, the effects of local instabilities, including creeping, tearing, or rupturing, can be observed, providing valuable insights into the discontinuous mechanisms of failure. In principle, two different options exist after finishing the reconstruction of a hernia: either the components exhibit low cyclic loading with alternating elastic and plastic behavior, finally leading to rupture, or tissue, mesh, and fixation cycle into shakedown, where they take the load at a certain stretch level with purely elastic behavior[25,26]. At this stage, the detailed analysis of the shakedown process in mesh-augmented human tissues and the effects of plastic strain accumulation during wound healing and scar formation is still in the early stages of the investigation.

To reach shakedown and permit stable collagen formation, the mesh size must be adapted to the hernia size and the mesh retention coefficient. The needs of individual patients can be assessed and taken into account. Fixation is used to reach the required stability. Regional load distribution can be achieved by quilting seams[46]. The conceptual design of a durable abdominal wall reconstruction can be applied by every surgeon[2-4]. After three years, over 160 patients consecutively operated on in four different hospitals by ten surgeons have no recurrence. The patients are back in their normal life, pain-free back at work if under 62 years of age. Insurance companies save money on compensation and on redo surgery once biomechanical considerations are more widespread and applied to abdominal wall reconstruction.

Destructive testing under dry conditions is often performed to advance hernia repair[47]. The force required is usually more than one megapascal[48]. Since this load is in excess of 7,500 mmHg, high-velocity shocks are modeled. Such impacts simulate the feet-first passage of a parachutist through a roof. Under these conditions, injuries to the lumbar spine and lower extremities predominate, with less than 2% trauma to the abdominal wall[49]. As shown above, cyclic pulse load simulating coughing or the Valsalva maneuver should guide future endoscopic and other technical developments. Surgeons should take the opportunity to gain knowledge about recent advances in basic and clinical research on the biomechanics of mesh repair of the herniated abdominal wall[50]. A recipe for the clinical application and practical examples are given in another contribution in the Special Issue[18].

FUTURE DIRECTIONS

More materials need to be tested and classified with cyclic load. A future policy for market access of repair material should include cyclic load bench testing. A tailored approach to incisional hernia repair should consider biomechanical aspects.

DECLARATIONS

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Author’s contributions

Designed the project, gathered the funds, and conducted most of the experiments: Nessel R, Kallinowski F
Conducted the rest of the experiments or directed the laboratory work: Lesch C
Built and maintainance of the bench test: Vollmer M

Availability of data and materials

All research and patient data are achieved in the Department of Surgery, University Hospital of Heidelberg, D-69120 Heidelberg, Germany, General and in the General, Visceral and Pediatric Surgery, SLK Klinikum Am Gesundbrunnen, D-74078 Heilbronn, Germany. Upon request and in accordance with European and German law regarding the disclosure, the data will be made available.

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Conflicts of Interest

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Ethical approval and consent to participate

Animal tissue was used in the bench test studies. The use of the tissues was permitted by Bürgeramt Veterinärwesen der Stadt Heidelberg according to European law with the permission DE 08 221 1018 21. The studies involving human participants were reviewed and approved by the Ethics Committee of the

Heidelberg University vote S-522/2020.The authors willingly participated in the study, exercising their own free will. The patients/participants provided their written informed consent to participate in the studies reported here.

Consent for publication
Not applicable.

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