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EPIDEMIOLOGY

The influence of reconstruction choice and inclusion of radiation therapy on functional shoulder biomechanics in women undergoing mastectomy for breast cancer

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Abstract

Purpose The functional implications of reconstructing the breast mound with a latissimus dorsi (LD) flap or placing an implant under the pectoralis major (PM) muscle is complicated by potential comorbidities from disinserting these muscles and adjuvant radiotherapy. We utilized novel robot-assisted measures of shoulder stiffness and strength to dissociate how breast reconstruction choice and inclusion of radiation therapy impact shoulder morbidity in post-mastectomy reconstruction patients.

Methods Shoulder strength and stiffness were collected from 10 irradiated LD flap breast reconstruction patients, 14 two-stage subpectoral implant reconstruction patients (subpectoral), and 10 irradiated deep inferior epigastric perforator (DIEP) flap patients an average of 659 days post-reconstruction. Univariate ANOVAs examined surgical group differences in strength and stiffness.

Results There were main effects of surgical group on vertical adduction, vertical abduction, and internal rotation strength. The LD flap group was significantly weaker than the subpectoral group in all measures and significantly weaker than the DIEP group during vertical adduction. There was also a main effect of surgical group on vertical adduction stiffness, where the LD group exhibited significantly reduced stiffness while producing vertical adduction torque. No significant differences between the subpectoral and DIEP groups existed for any measure of shoulder strength or stiffness.

Conclusions Disinsertion of the LD, not the disinsertion of the PM or radiotherapy, contributes to strength deficits following LD flap breast reconstructions. The combined disinsertion of the PM and LD compromises shoulder stability in the vertical plane. Shoulder function should be a focal point of the surgical decision-making process and postsurgical care.

Keywords Postoperative complications · Shoulder stiffness · Latissimus dorsi · Implant reconstruction · Autologous reconstruction

Introduction

Increasing mastectomy rates have been driven in part by more breast cancer patients opting for bilateral mastectomy with reconstruction, with approximately 107,000 post-mastectomy breast reconstruction surgeries performed in the USA annually [1]. Patients that undergo mastectomy without reconstruction can experience psychosocial disturbances and problems with body image and sexuality [2]. A breast reconstruction procedure restores the form, appearance, and feel of the breast mound [3] and provides psychosocial and quality of life benefits [4]. Identifying the functional implications of mastectomy and breast reconstruction is needed to optimize the quality of life of breast reconstruction patients,

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given the increasing survivorship with advances in early detection and therapy [5].

Various breast reconstruction procedures are available to mastectomy patients to restore the breast mound [6–8]. An immediate two-stage implant-based breast reconstruction accounts for ~60% of all post-mastectomy reconstructions [8]. This procedure disinserts the pectoralis major (PM) from the ribs and lower sternum to accommodate a subpectoral tissue expander and eventual implant. Because implant reconstructions have relatively high failure rates after radiation therapy [9–11], the latissimus dorsi (LD) is used as a myocutaneous flap in combination with expanders and implants to restore the breast mound for post-mastectomy patients after radiation therapy [12]. This procedure fully disinserts the LD from the spine and transposes the flap to the chest for additional tissue coverage of an implant. The PM muscle can also be disinserted during LD breast reconstruction for implant coverage with both muscle flaps. Alternatively, irradiated patients can be reconstructed with a deep inferior epigastric perforator (DIEP) flap. The DIEP flap recreates the breast mound without an implant by transferring the abdominal tissue to the chest and using microsurgical anastomotic techniques to reestablish blood supply to the flap. A DIEP flap reconstruction requires minimal division of PM fibers over the 3rd or 4th rib near the sternum to access the internal mammary recipient vessels but does not include disinsertion of any shoulder muscles.

Disinsertion of the PM and/or LD can have long-term functional consequences for patients undergoing mastectomy with breast reconstruction. These muscles are critical for maintaining healthy shoulder joint stability [13] and have similar functional demands, including shoulder adduction and internal rotation [12, 14–19]. The disinsertion of both muscles produces strength and mobility deficits in up to half of all LD flap patients [14, 15, 17, 20–28]. LD flap patients also self-report shoulder instability, even in the absence of strength or mobility deficits [21]. Since reduced stability negatively impacts quality of life [29–31], objective measures of shoulder stability following breast reconstruction can provide new insights to improved surgical decision-making and postoperative care. Furthermore, the functional implications of the inclusion of post-mastectomy radiation therapy on the treated shoulder of reconstruction patients are unclear, as patients undergoing radiotherapy and mastectomy can exhibit reduced mobility and strength [32, 33].

The objective of this study was to determine how breast reconstruction choice influences the long-term functional integrity of the shoulder joint using objective robot-assisted measures of shoulder joint stability ('stiffness') and strength. LD flap reconstruction patients were compared to subpectoral implant reconstruction patients and DIEP flap patients to control for the effects of additional release of the PM and radiation therapy, respectively. We hypothesized that LD flap patients would exhibit significantly reduced strength and active stiffness in vertical adduction when compared to both the two-stage implant and DIEP flap patients.

Materials and methods

Participants

A retrospective medical chart review from a single surgeon's practice retrospectively identified 155 women eligible for this study, of which 34 women consented to participate in a single experimental session (Table 1). We examined women undergoing one of three post-mastectomy breast reconstruction procedures: subpectoral implant, LD flap, and DIEP flap. Fourteen patients underwent an immediate two-stage subpectoral implant with the PM muscle elevated during surgery, but did not require radiation therapy. Ten LD flap patients and 10 DIEP flap patients that required radiation therapy underwent delayed breast reconstruction in order to complete radiation therapy prior to their reconstructive surgery. The LD flap patients had an implant reconstruction where both the LD muscle and PM muscle were elevated during surgery. The DIEP flap patients had an autologous reconstruction that did not require any upper extremity muscles to be elevated during surgery. A minimum of 12 months was required after completion of breast reconstruction before biomechanical assessments. The University of Michigan's Institutional Review Board approved all study procedures (HUM00114801), and participants provided written informed consent prior to data collection. Participants with previous neuromuscular or orthopedic disorders affecting the upper limb were excluded from the study.

Experimental setup

Participants were secured to an adjustable chair (Biodex Medical Systems, Shirley, New York) with torso movement restricted using a chest strap and cushioned plates positioned along the lower back and sides. A custom-made plastic cast extending from the hand to the shoulder attached the participant's examined shoulder to a computer-controlled brushless servomotor (Baldor Electric Company, Fort Smith, AR) (Fig. 1). Within the cast, the elbow was fixed at 90° and the wrist was neutral. Movement of the scapula was not restricted. The center of rotation of the glenohumeral joint was aligned to the motor's axis of rotation. Shoulder joint torques were measured using a six degrees-of-freedom load cell (JR3, Inc., Woodland, CA) attached between the crank arm of the motor and the cast. Our measurement coordinate system was defined using established biomechanical standards [34].

Table 1 Mean (standard error) participant demographics for each of the three experimental groups: latissimus dorsi flap (LD Flap), two-stage subpectoral implant (Subpectoral), and deep inferior epigastric perforator flap (DIEP Flap)

	LD flap	Subpectoral	DIEP flap	LD versus subpectoral p	LD versus DIEP p
Number of participants	10	14	10		
Age (years)	53 (3.3)	49 (2.5)	51 (2.8)	0.310	0.607
Height (m)	1.62 (0.01)	1.64 (0.01)	1.65 (0.02)	0.221	0.201
Weight (kg)	75 (5.3)	71 (2.9)	84 (5.6)	0.534	0.236
BMI (kg/m^2)	29 (1.9)	26 (1.1)	31 (2.2)	0.325	0.425
Days postoperative from reconstruction	670 (44)	588 (41)	788 (81)	0.186	0.224
Dominant/non-dominant limb	7/3	10/4	5/5		
Radiation therapy (yes/no)	10/0	0/14	10/0		
Chemotherapy (yes/no)	8/2	5/9	8/2		
Axillary lymph node dissection (ALND)	3	0	4		
Sentinel lymph node biopsy (SLNB)	4	12	4		
ALND + SLNB	3	0	0		
# of nodes removed					
0	0	3	2		
1–3	3	5	0		
4–6	2	3	0		
7+	4	1	7		

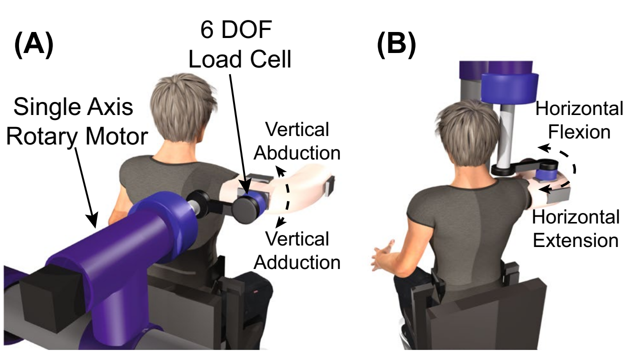

Fig. 1 Schematic of experimental setups. A single-axis rotary motor perturbed a participant's examined shoulder in while a six-degree-of-freedom load cell measured resultant torques in all three dimensions. Visual feedback was provided via LCD screen. **a** The rotary motor was positioned to move the arm in the vertical plane while participants were relaxed or generating shoulder torques in vertical adduction (downwards) or vertical abduction (upwards). **b** The rotary motor was positioned to move the arm in the horizontal plane while participants were relaxed or generating shoulder torques in horizontal flexion (forward) or horizontal extension (backwards)

Experimental protocol

Participants performed maximal voluntary contractions (MVC) in the positive and negative directions of each measurement plane (vertical adduction/abduction; internal/external rotation; horizontal flexion/extension) at the beginning of the experiment to measure and normalize the remaining trials to each participant's strength. Participants were then examined in two separate shoulder planes of motion (vertical adduction/abduction or horizontal flexion/extension) in a random order (Fig. 1). The shoulder remained in the same posture in all trials.

The stiffness of the shoulder joint was measured in each plane by measuring the resultant shoulder torque as the motor applied a series of small, stochastic perturbations with a pseudo-random binary sequence (0.06 rad amplitude and 150 millisecond switching interval). Each perturbation trial lasted for 60 s, during which the participants were asked to remain relaxed (0% MVC) or to maintain a constant torque scaled to ± 10% MVC for the given direction. Participants used visual feedback to assist in maintaining the prescribed torque. One passive trial was included at the beginning of each motor configuration to acclimate the participants to the sensation of being perturbed. We repeated each perturbation testing condition for six total trials per motor configuration and then repeated these procedures for the remaining motor configuration. In total, each participant performed 14 perturbation trials.

Data and statistical analysis

Shoulder stiffness was estimated using system identification [35, 36] using MATLAB (v2016a, Mathworks, Inc, Natick, MA, USA). For each trial, we first measured joint impedance by measuring the dynamic relationship between imposed change in joint angle in a given plane and the resultant torque [37]. Joint impedance was quantified as a frequency response function from 0 to 10 Hz. A numerical optimization parameterized this frequency response function using a second-order linear system consisting of inertial (*I*), viscous (*B*), and stiffness (*K*) components [36]. The current study only reports the stiffness component as this is the most clinically relevant parameter for assessing the stability of the shoulder joint.

All statistical procedures were performed in SPSS (v24, IBM Corporation, Chicago, IL, USA). The datasets during and/or analyzed during the current study are available from the corresponding author on reasonable request. Differences in demographic measures (age, height, mass, BMI, days post-reconstruction surgery) between each experimental group (LD flap vs. subpectoral; LD flap vs. DIEP) were investigated using t tests. We tested our hypothesis that the LD flap group would exhibit reduced shoulder strength and stiffness in the vertical plane when compared to the subpectoral group and DIEP groups using univariate ANOVAs. Our outcome measures were strength in one of six directions (vertical adduction, vertical abduction, horizontal flexion, horizontal extension, internal rotation, external rotation) and stiffnesses in two different directions (vertical and horizontal) and three different activation conditions (at rest, adduction/flexion, and abduction/extension). Surgical group (subpectoral implant, LD flap or DIEP flap) was a fixed factor. Bonferroni-corrected multiple comparisons were used to analyze significant main effects. All analyses utilized a significance level of $p < 0.05$. Effect sizes (partial η^2) were calculated to distinguish between small (0.010–0.059), moderate (0.060-0.0139), and large (≥ 0.140) clinically relevant differences [38].

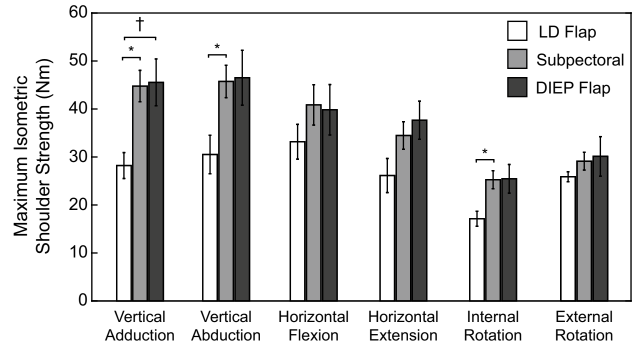

Fig. 2 Mean shoulder strength across three reconstructive surgeries. Participants performed maximal isometric shoulder torques in the positive and negative directions in the vertical (vertical adduction, vertical abduction), horizontal (horizontal flexion, horizontal extension), and rotation planes (internal rotation, external rotation). Bars represent mean ± standard error for the maximal isometric shoulder strength (Nm) of each experimental group (*LD* latissimus dorsi flap; Subpectoral two-stage subpectoral implant, *DIEP* deep inferior epigastric perforator flap). *Denotes significant difference between the LD and implant groups. †Denotes significant difference between the LD and DIEP groups

Results

Demographics

Patient demographics are shown in Table 1. There were no significant differences in age, height, weight, BMI, or days post-reconstruction between the LD flap group and either the subpectoral or the DIEP flap groups.

Shoulder strength

There was a significant main effect of surgical group on vertical adduction ($F_{2,33} = 6.326$, $p = 0.005$, $\eta^2 = 0.28$), vertical abduction ($F_{2,33} = 4.047$, $p = 0.021$, $\eta^2 = 0.20$), and internal rotation strength ($F_{2,33} = 4.316$, $p = 0.022$, $\eta^2 = 0.21$) (Fig. 2). Post hoc comparisons revealed that during vertical adduction, the LD flap group was 22.7% weaker than the subpectoral group ($p = 0.009$) and 23.5% weaker than the DIEP flap group ($p = 0.014$). Furthermore, the LD flap group was 20.0% weaker than the subpectoral group ($p = 0.044$) during vertical abduction. The LD flap group was also 19.2% weaker than the subpectoral group during internal rotation ($p = 0.034$). The subpectoral and DIEP flap groups did not differ (all $p > 0.99$). No significant differences were observed between the groups for horizontal flexion ($F_{2,33} = 0.815$, $p = 0.451$, $\eta^2 = 0.05$), horizontal extension ($F_{2,33} = 2.649$, $p = 0.086$, $\eta^2 = 0.14$), or external rotation ($F_{2,33} = 0.691$, $p = 0.508$, $\eta^2 = 0.04$) strength.

Shoulder stiffness

There was a significant main effect of surgical group on shoulder stiffness as participants produced vertical adduction torque ($F_{2,33} = 5.655$, $p = 0.008$, $\eta^2 = 0.27$) (Fig. 3). Post hoc analyses revealed that during this condition, the LD flap group exhibited 24.6% lower shoulder stiffness than the DIEP group ($p = 0.01$). Although the LD flap participants experienced a greater volume of muscle disinsertion than the subpectoral group, the groups were not significantly different while producing vertical adduction ($p = 0.721$) torque. No significant differences were observed between the groups when producing vertical abduction ($F_{2,33} = 0.995$, $p = 0.381$, $\eta^2 = 0.06$), horizontal flexion ($F_{2,33} = 0.597$, $p = 0.557$, $\eta^2 = 0.04$), or horizontal extension ($F_{2,33} = 1.002$, $p = 0.379$, $\eta^2 = 0.06$) torques. All three experimental groups also exhibited similar shoulder stiffness at rest in the vertical ($F_{2,33} = 1.034$, $p = 0.367$, $\eta^2 = 0.06$) and horizontal planes ($F_{2,33} = 0.096$, $p = 0.908$, $\eta^2 = 0.01$).

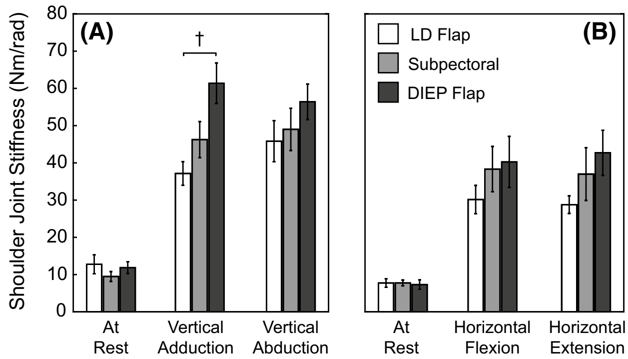

Fig. 3 Mean shoulder stiffness across three reconstructive surgeries. Participants were perturbed in the vertical (**a**) and horizontal (**b**) planes of motion. During perturbation trials, participants were asked to remain relaxed (while at rest) or to maintain torques scaled to − 10% MVC (vertical/horizontal flexion) and + 10% MVC (vertical/horizontal extension) in the respective planes of motion. Bars represent mean ± standard error shoulder stiffness (Nm/rad) for each experimental group (*LD* latissimus dorsi flap, *Subpectoral* two-stage subpectoral implant, *DIEP* deep inferior epigastric perforator flap). †Denotes significant difference between the LD and DIEP groups

Discussion

This study dissociated the effects of reconstruction choice and the inclusion of radiation therapy in women with breast cancer that undergo mastectomy and reconstruction. Our results provide the first objective evidence that LD flap reconstructions diminish shoulder stability. Irradiated patients that have the PM disinserted during a LD flap reconstruction exhibited significantly reduced active shoulder stability in vertical adduction when compared to irradiated DIEP flap patients who had no muscle disinsertion. Our results also indicate that the disinsertion of the LD and PM leads to greater overall shoulder strength deficits than the disinsertion of the PM alone during a standard two-stage breast reconstruction. Finally, the combined disinsertion of the LD and PM in irradiated patients reduces shoulder strength when compared to irradiated DIEP flap patients with no further muscle disinsertion. These results confirm that LD flap reconstruction patients experience worse long-term shoulder morbidity than other breast reconstruction patients and that postsurgical interventions are needed to restore shoulder strength and stability in LD flap patients. Our results also suggest that the combined disinsertion of the PM and LD should be avoided when it is possible to complete the procedure utilizing the LD alone.

Objective measures of shoulder strength provide insights into the degree of impairment following LD flap reconstruction. Prior investigations of functional outcomes in LD flap reconstruction focus on the first 12 months post-reconstruction, when the acute effects of the surgery are present [15, 17, 20, 22, 24, 26, 39]. Only three prior studies have directly measured shoulder strength greater than 6 months post-reconstruction. When compared to pre-surgical levels and the non-operated shoulder, shoulder vertical adduction, extension, and internal rotation strength remains reduced more than 4 years post-LD flap breast reconstruction [14, 21]. When compared to healthy controls, LD flap patients suffer from reduced isometric shoulder adduction, extension, and internal rotation strength 3.5 years post-reconstruction and radiotherapy [40]. Our findings agree with previous reports that LD flap reconstructions compromise shoulder strength. We found the LD group exhibited reduced strength when compared to the subpectoral group, who underwent disinsertion of the PM but no adjuvant radiotherapy, and the DIEP group, who had adjuvant radiotherapy. This supports prior observations that strength loss observed following LD flap breast reconstructions is more related to the loss of the latissimus dorsi than radiotherapy [40].

Our study used novel assessments of shoulder stiffness to measure the mechanical stability of the shoulder joint following breast reconstruction. These stiffness measures quantify a patient's ability to stabilize their arm [29] and provide insights into the health and function of the shoulder during activities of daily living. At rest, stiffness quantifies the stability provided by passive soft tissues acting on the shoulder, such as ligament, tendon, and muscle [41]. All surgical groups exhibited similar measures of stiffness at rest in both the vertical and horizontal planes. These results are unsurprising, as muscle constitutes a small contribution to overall joint stiffness at rest [41]. Under active conditions, shoulder stiffness is largely attributable to the coordinated activations of shoulder muscles [41–43]. We observed altered active joint stiffness during vertical adduction following disinsertion of the LD. This reduction in stiffness is likely due to the combined disinsertion of the LD and PM, as the subpectoral and LD flap groups exhibited similar stiffnesses during vertical adduction. These results agree with previous reports of reduced stability following the disinsertion of the LD [21].

Clinical practice assumes that the musculoskeletal system can adapt and compensate for lost function following muscle disinsertion in reconstructive surgery [19, 44–46]. The LD and PM are two of three muscles that contribute significantly to shoulder vertical adduction. Therefore, the disinsertion of both muscles leaves little room for compensation in vertical adduction from intact musculature [13]. The LD also contributes substantially to shoulder horizontal extension, and therefore, its disinsertion should theoretically influence horizontal extension stiffness. However, our LD flap group exhibited similar horizontal extension stiffness to both the subpectoral and DIEP flap groups, suggesting an increased contribution from remaining musculature. The teres major, infraspinatus, and subscapularis muscles, which contribute to shoulder stability using similar lines of action as the latissimus dorsi when the arm is abducted to 90° [12], are the most likely muscles to compensate. Additionally, the intact clavicular fiber region of the PM contributes to shoulder function in the horizontal plane [47].

Our study has certain limitations. First, our cross-sectional study design does not allow for the longitudinal effects of LD flap breast reconstructions to be fully appreciated. We mitigated this limitation by using well-defined control groups to control for the disinsertion of the PM and the inclusion of radiation therapy. Theoretically, the opposite shoulder could serve as a control for each patient. However, experimental time constraints and variability in arm dominance, history of injury to the opposite arm/shoulder, and patient preference for completing unilateral or bilateral surgeries made it difficult to use the opposed shoulder as a true control. Our experimental procedures only assessed the shoulder in a single posture, but the chosen posture should illicit the greatest contributions of the PM and LD to shoulder function based on their moment arms [48]. The LD was fully disinserted from the spine in all LD patients, but there might have been variability in the amount that the PM was disinserted for each participant. We attempted to minimize this variability by recruiting patients from a single surgeon. The vast majority of patients included in the current study received radiation therapy from outside providers, and therefore, we had limited access to their radiation therapy records. We were only able to control for the inclusion of radiotherapy in their management of breast cancer and could not control for radiation dose or field design.

In conclusion, we demonstrated that the disinsertion of the LD, not the disinsertion of the PM muscle or radiotherapy, contributes to the commonly observed strength deficits following LD flap breast reconstruction. Our findings also provide objective evidence that the combined disinsertion of the PM and LD compromises LD flap patients ability to stabilize their shoulder joint in the vertical plane. When possible, consideration should be given to harvesting only the LD for coverage of implants as opposed to the LD and PM. Together, these findings suggest that shoulder function should be included in the surgical decision-making process and that postsurgical care should aim to improve both shoulder strength and stability.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the University of Michigan Institutional Review Board and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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