

The Effects of Kinect-Enhanced Lymphatic Exercise Intervention on Lymphatic Pain, Swelling, and Lymph Fluid Level

Integrative Cancer Therapies
Volume 20: 1–14
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DOI: 10.1177/15347354211026757
journals.sagepub.com/home/ict



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Abstract

Background: *The-Optimal-Lymph-Flow* (TOLF) intervention aims to promote lymph flow through therapeutic lymphatic exercises to relieve lymphatic pain, swelling, lymphedema symptoms, and to decrease lymph fluid levels among breast cancer survivors. To enhance the efficacy of the TOLF intervention, an innovative, intelligent, Kinect-enhanced lymphatic exercise intervention (Kinect-TOLF) was developed to teach patients to perform the lymphatic exercises correctly. **Objectives:** This feasibility trial aimed to determine the feasibility, usability, and effects of the Kinect-TOLF on lymphatic pain, swelling, lymphedema symptoms, and lymph fluid levels. **Methods:** A single-arm feasibility trial with a pre- and post-test design was employed to recruit 30 breast cancer survivors with persistent lymphatic pain or swelling. Patients received a single training session to learn how to perform the lymphatic exercises using the Kinect-TOLF program. Descriptive statistics, Wilcoxon signed-rank tests, *t*-test, Spearman's rank correlation coefficients, linear regressions, and Cohen's *d* were performed for data analysis. Qualitative data were assessed for common themes. **Results:** The Kinect-TOLF was effective in training patients to perform the lymphatic exercises correctly with high user satisfaction. Significant reductions were found in scores of lymphatic pain ($Med_{\Delta} = -1.00$, $CI = [-1.5, -0.1]$, $P = .004$), arm/hand swelling ($Med_{\Delta} = -1.00$, $CI = [-1.5, -0.5]$, $P = .004$), total swelling ($Med_{\Delta} = -1.5$, $CI = [-2.0, -1.0]$, $P = .003$), number of lymphedema symptoms ($M_{\Delta} = -3.8$, $CI = [-5.5, -2.1]$, $P < .001$), and lymphedema symptom severity ($M_{\Delta} = -5.3$, $CI = [-9.5, -1.1]$, $P = .016$). A significant reduction in lymph fluid levels was found in mean L-Dex scores ($M_{\Delta} = -2.68$, $CI = [-4.67, -0.69]$, $P = .010$). Greater decrease in mean L-Dex scores were found in patients with abnormal lymph fluid levels ($L-Dex \geq 7.1$) ($M_{\Delta} = -5.19$, $CI = [-1.75, -8.63]$, $P = .008$). Patients' qualitative feedback supported the results of the study. **Conclusions:** The Kinect-TOLF is safe, feasible, and effective in reducing lymphatic pain, swelling, lymphedema symptoms, and in decreasing lymph fluid levels. Future research should focus on a randomized clinical trial to confirm the unique or synergistic efficacy of the Kinect-TOLF in comparison with current lymphedema treatment and other forms of exercises or movement therapy. This study was registered in ClinicalTrials.gov with US ClinicalTrials.gov Identifier: NCT03999177.

Keywords

lymphatic, pain, swelling, lymphedema, lymph fluid, breast cancer, symptoms

Submitted February 2, 2021; revised May 12, 2021; accepted June 2, 2021

Introduction

Lymphatic pain, swelling, and lymphedema symptoms are ongoing debilitating adverse effects of cancer treatment that elicit distress and negative impacts on breast cancer survivors' quality of life (QOL).¹⁻³ Breast cancer survivors have a

compromised lymphatic system due to cancer treatment,⁴⁻⁶ resulting in an accumulation of lymph fluid in the ipsilateral body or upper limb.⁷⁻⁹ The accumulation of lymph fluid leads to a chronic and co-occurring variety of pain sensations (i.e., pain/aching/soreness) in the ipsilateral upper limb



or body defined as lymphatic pain and other symptoms related to fluid accumulation defined as lymphedema symptoms.⁷⁻⁹ Both swelling and lymphedema are caused by an abnormal accumulation of lymph fluid in the ipsilateral body or upper limb.⁷ Swelling often refers to patient-reported symptom. Lymphedema is often defined as an increased limb size or girth comparing affected (or lymphedematous) and unaffected limbs.⁷⁻⁹

While lymphatic pain, swelling, and lymphedema symptoms are most common in patients with a diagnosis of lymphedema,⁷ more than 50% of breast cancer survivors without a diagnosis of lymphedema also report daily co-occurring lymphatic pain, swelling, and lymphedema symptoms.⁷⁻⁹ For breast cancer survivors without a diagnosis of lymphedema, the experience of lymphatic pain, swelling, and lymphedema symptoms is a cardinal sign of an early stage of lymphedema because these symptoms often precede changes in limb size or girth and a lymphedema diagnosis.^{8,9} Breast cancer survivors who report pain on the affected ipsilateral upper limb or body are nearly twice as likely to develop lymphedema.⁷ Without timely intervention in this early stage, lymphedema can progress into a chronic condition that no surgical or medical interventions can cure.^{10,11} Thus, the effective management of lymphatic pain, swelling, and lymphedema symptoms is needed for breast cancer survivors with or without a diagnosis of lymphedema.

Pharmacological interventions (eg, NSAIDs, opioids) and behavioral strategies are commonly used for pain control in cancer patients.¹¹⁻¹⁶ Lymphedema treatments (e.g., manual lymph drainage, physical therapy, compression garments, upper extremity exercise, yoga) are used to control swelling.¹¹ Research is limited on the efficacy of interventions that target physiological factors (e.g., the compromised lymphatic drainage) to manage lymphatic pain, swelling, and lymphedema symptoms. *The-Optimal-Lymph-Flow* (TOLF) intervention, a patient-centered and nurse-led self-care program, aims to promote lymph flow through the performance of therapeutic lymphatic exercises and strategies to achieve nutrition-balanced, portion-appropriate diet, adequate hydration, and proper sleep to minimize the risk of lymphedema.¹⁷⁻¹⁹ The therapeutic lymphatic exercises include a set of muscle-tightening deep breathing and muscle-tightening pumping and shoulder exercises. Table 1

describes the physiologic rationale for each lymphatic exercise. The efficacy of the TOLF intervention to prevent lymph fluid accumulation was demonstrated in a clinical trial with 140 patients after breast cancer surgery.¹⁷ The efficacy of TOLF for lymphatic pain was demonstrated in a 12-week pilot feasibility clinical trial that used a mobile avatar-based coaching system to deliver the TOLF intervention.¹⁸

To enhance the efficacy of the TOLF intervention, we developed and tested a Kinect-enhanced lymphatic exercise intervention system (Kinect-TOLF) that uses a Microsoft Kinect sensor to capture both color and depth information while the patient is performing the lymphatic exercises following an avatar on a screen (Figure 1).²⁰⁻²² The Kinect-TOLF accurately aligns a user's motion sequence with the standard motion sequence and evaluates the "correctness" of the user's movements in real time. This approach facilitates instantaneous feedback to the user while the user is performing each exercise.

We conducted a single-arm feasibility clinical trial with a pre- and post-test design to assess the feasibility and usability of the Kinect-TOLF to deliver a therapeutic lymphatic exercise intervention to breast cancer survivors. The objectives of this trial were to: (1) evaluate the Kinect-TOLF in breast cancer survivors in terms of feasibility (i.e., study accrual and protocol adherence) and usability (i.e., ratings of training quality, system quality, and behavioral intention of using the Kinect-TOLF); and (2) test the efficacy of the Kinect-TOLF on reductions in lymphatic pain, swelling, lymphedema symptom occurrence (i.e., number and severity of symptoms), and lymph fluid levels. We hypothesized that a single session of Kinect-TOLF intervention would lead to significant reductions in lymphatic pain, swelling, lymphedema symptom occurrence (i.e., number and severity of symptoms), and lymph fluid levels. This study was registered in ClinicalTrials.gov with US ClinicalTrials.gov Identifier: NCT03999177.

Methods

Ethical Approval

This study (S19-00222) was approved by the Institutional Review Board of NYU Langone Health, in New York, United States.

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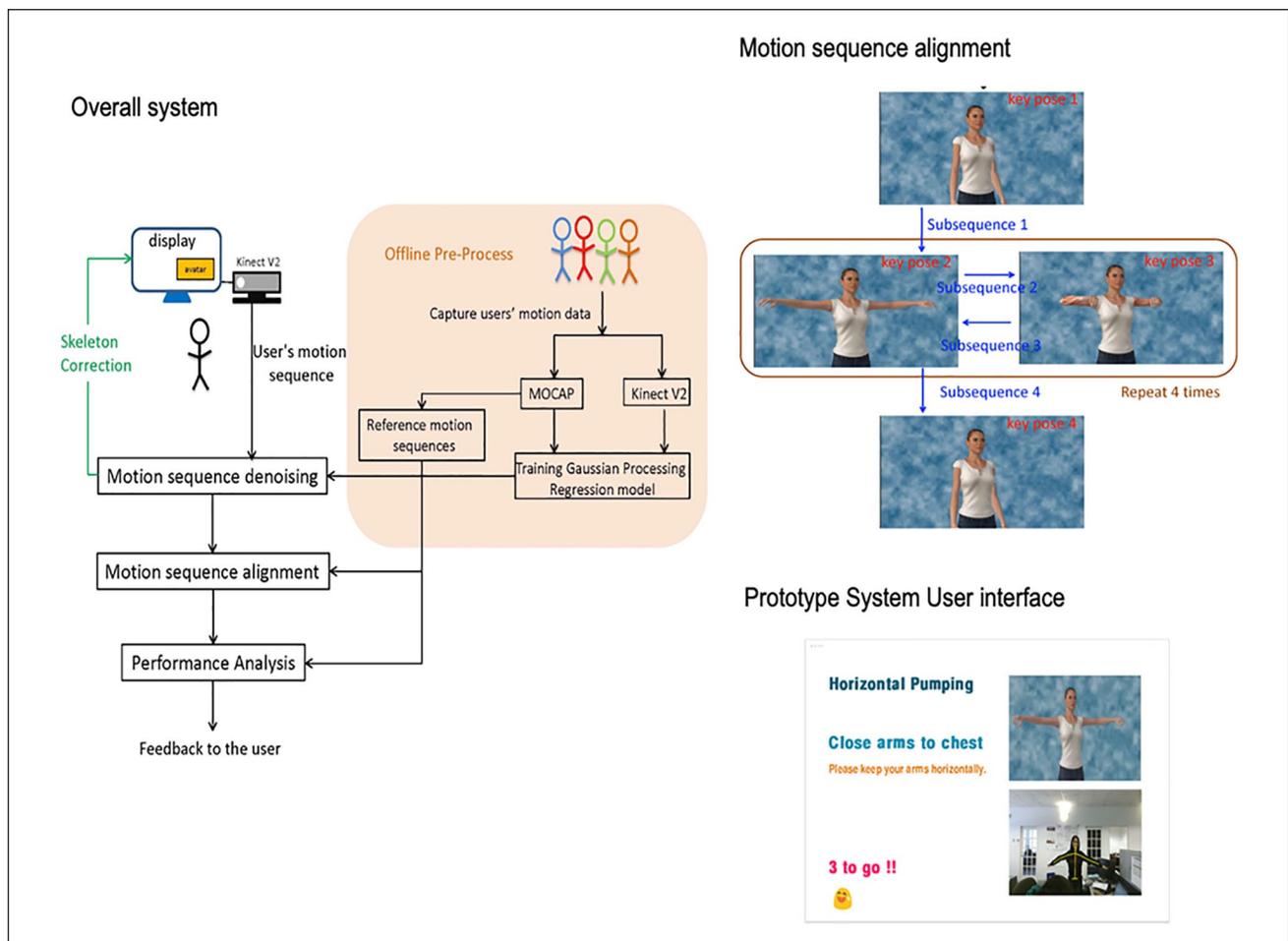
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Table 1. Kinect-Enhanced Lymphatic Exercise Intervention (Kinect-TOLF).

Lymphatic exercises	Physiological rationales
Muscle-tightening deep breathing	Whole body lymph fluid has to be drained through the lymphatic ducts above the heart. Muscle-tightening-deep-breathing stimulates lymphatic ducts to promote lymph fluid draining. Lymph fluid drains when muscles move. Muscle-tightening-deep-breathing creates the whole body muscle movements that create muscle milking and pumping action and help drain lymph fluid. Deep breathing enhances muscle pumping in the upper body by contracting the external intercostal muscles, the accessory muscles of inspiration, and the diaphragm during inspiration and the internal intercostal muscles and abdominal muscles during expiration. Deep breathing decreases oxidative stress and oxygenates body tissues. It decreases inflammation and promotes wound healing.
Muscle-tightening pumping Over-the-head pumping Horizontal pumping Push-down pumping	Muscle-tightening pumping exercises create arm muscle milking and pumping, including the main anterior upper arm muscles (biceps brachii, brachialis, coracobrachialis), the posterior muscle of triceps brachii, and deltoid muscle (ie, the anterior deltoid, lateral deltoid, and posterior deltoid). The pumping of these muscles increases lymph fluid flow and decreases the fluid build-up in the arms. Muscle-tightening pumping exercises build the arm muscles that help lymph fluid flow and drain.
Shoulder exercises Shoulder rolls Clasp and spread Reach to the sky	Improved limb mobility facilitates local muscle movements that create muscle milking and pumping to promote lymph fluid flow and drainage. Shoulder exercises create arm muscle milking and pumping by moving the main anterior upper arm muscles (biceps brachii, brachialis, coracobrachialis), the posterior muscle of triceps brachii, and deltoid muscle (ie, the anterior deltoid, lateral deltoid, and posterior deltoid).

**Figure 1.** Kinect-enhanced lymphatic exercise intervention.

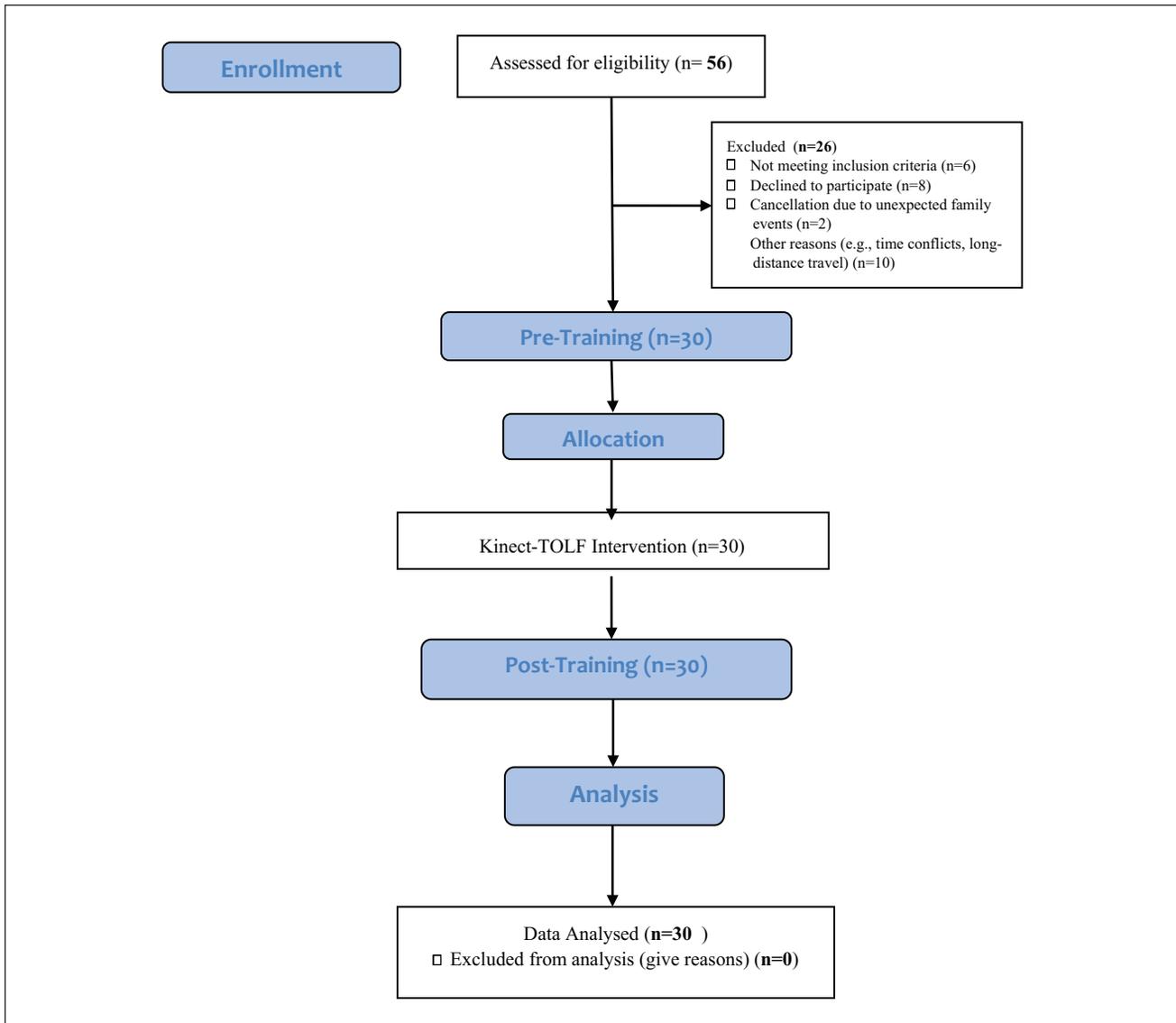


Figure 2. Patient flow chart.

Study Design

This study was a single-arm, single-center, feasibility clinical trial that utilized a pre- and post-test design. Feasibility of the study was defined as study accrual ($N=30$) in 6 months of recruitment and $>80\%$ of protocol adherence defined as participants' completion of the Kinect-TOLF training for lymphatic exercises. We assessed the usability of the Kinect-TOLF in terms of the extent that the user interface met Nielsen's principles for usability (i.e., learnability, efficiency, memorability, errors, satisfaction).²³⁻²⁵

Setting

The study was conducted in a nursing research laboratory located in the breast cancer clinic of New York University

Perlmutter Cancer Center, a National Cancer Institute designated cancer center in New York City, US.

Participants

Participants were recruited from among the consecutively-identified breast cancer survivors who reported persistent lymphatic pain or swelling in the ipsilateral upper limb or body at least 12 weeks after breast cancer surgery during routine clinical visits. A total of 30 patients were recruited from July 26 to September 3, 2019. All patients signed a written consent. Figure 2 presents the Patient Flow Chart.

Patients who met the following inclusion criteria were recruited. Inclusion criteria were women who (a) had

received surgical treatment for Stage I-III breast cancer, including mastectomy, lumpectomy, sentinel lymph node biopsy (SLNB), SLNB plus lymph node dissection or axillary lymph node dissection (ALND);^{5,6} (b) reported persistent pain or swelling in the ipsilateral upper limb or body at least 12 weeks after surgery; (c) may or may not have had neoadjuvant or adjuvant therapy of chemotherapy or radiation; (d) may or may not have had a history of or being treated for lymphedema;^{5,6} and (e) were able to speak and understand English. Patients were excluded if they had (a) known metastatic disease, cancer recurrence, or lymphedema due to cancer recurrence, or other bulk disease in the thoracic or cervical regions; and (b) renal or heart failure, a cardiac pacemaker or defibrillator, artificial limbs, or were pregnant.

Sample Size

The primary objective of this study was to determine the feasibility and usability of the Kinect-TOLF. The end-users of the Kinect-TOLF are breast cancer survivors with persistent lymphatic pain or swelling. A relatively small sample size of 10 to 15 end-users is recommended for usability testing.^{23,24} A sample of 30 patients who represented the end-users of the breast cancer survivors with persistent lymphatic pain or swelling was appropriate for the feasibility^{26,27} and usability testing.^{23,24}

Study Procedures

Kinect for Windows SDK 2.0 was installed on a study laptop and the Kinect sensor was connected to the laptop. Prior to the Kinect-TOLF training session, demographic, and clinical data were collected, BMI and intervention outcomes were assessed. The intervention outcomes were assessed in the same order prior to and after training (i.e., lymphatic pain, arm/hand swelling, lymphedema symptoms, lymph fluid level). Upon the completion of the single training session, each patient was instructed to sit and rest for 5 minutes, followed by post training assessment of the intervention outcomes. In addition, patients were asked to complete the usability questionnaires and qualitative evaluation of the training. All the self-reported questionnaires were administered to the participants electronically via a study iPad connected to the study specific electronic database capture system. Two researchers who were not involved in the Kinect-TOLF training assessed patients' lymph fluid levels using a bioimpedance device independently prior to and after the training session.

To evaluate usability of the Kinect-TOLF, we completed a heuristic evaluation with each patient. A heuristic evaluation is a usability inspection method in which a relatively small group of end-users examine the extent to which a user interface meets Nielsen's principles for usability.^{23,24} These

principles include visibility of system status; the match between the system and the real world; user control and freedom; recognition rather than recall; and flexibility and efficiency of use.²³⁻²⁵ Each patient completed a set of specified tasks designed to explicate system features and freely explore the prototype. Then, patients completed a heuristic evaluation checklist that included ratings of the severity of heuristic violations (i.e., no usability problem, cosmetic problem, minor usability problem, major usability problem, usability catastrophe).

We used an iterative process to test the usability and acceptance of the Kinect-TOLF and refine the program based on patients' "think aloud" comments during the training sessions.^{19,23-25} The "think aloud" method generated data on patients' ongoing thought processes as they completed a set of training tasks designed to explicate system features.^{19,23-25} Only a few refinements were made based on patients' comments, such as motion synchronization when patients performed the exercises (Figure 3).

The Kinect-TOLF Lymphatic Exercise Intervention

As an essential component of *The-Optimal-Lymph-Flow* (TOLF) intervention,^{17,18} the Kinect-TOLF is an innovative and intelligent Kinect-enhanced lymphatic exercise intervention that teaches patients to perform correctly the lymphatic exercises (Table 1).¹⁷⁻²² The Kinect-TOLF is intelligent in that it can automatically detect whether a user is performing the set of lymphatic exercises correctly in real time and provide instantaneous feedback to the user while the user is following the avatar model in the video to perform the lymphatic exercises. This approach enhances patients' self-efficacy to perform the lymphatic exercises correctly. The therapeutic lymphatic exercises are safe and were found to be efficacious in prior studies.¹⁷⁻¹⁹ The Kinect-TOLF uses the Kinect v2 sensor that is commercially available and widely used in video games.²⁰⁻²² No foreseeable risks are associated with the use of the Kinect-TOLF.¹⁷⁻²² No injuries and complaints were reported with these exercises in previous studies¹⁷⁻¹⁹ as well as in this study. Each patient received a single training session to learn how to perform the lymphatic exercises using the Kinect-TOLF program. The training session ended when the patient was able to perform each of the 7 lymphedema exercises correctly using the Kinect-TOLF. The duration of the training session was 10 to 15 minutes.

Measures and Outcome Variables

Clinical and Demographic Information were collected from patients' self-reports and medical record reviews, including age, financial status, types of surgeries, time since surgery,

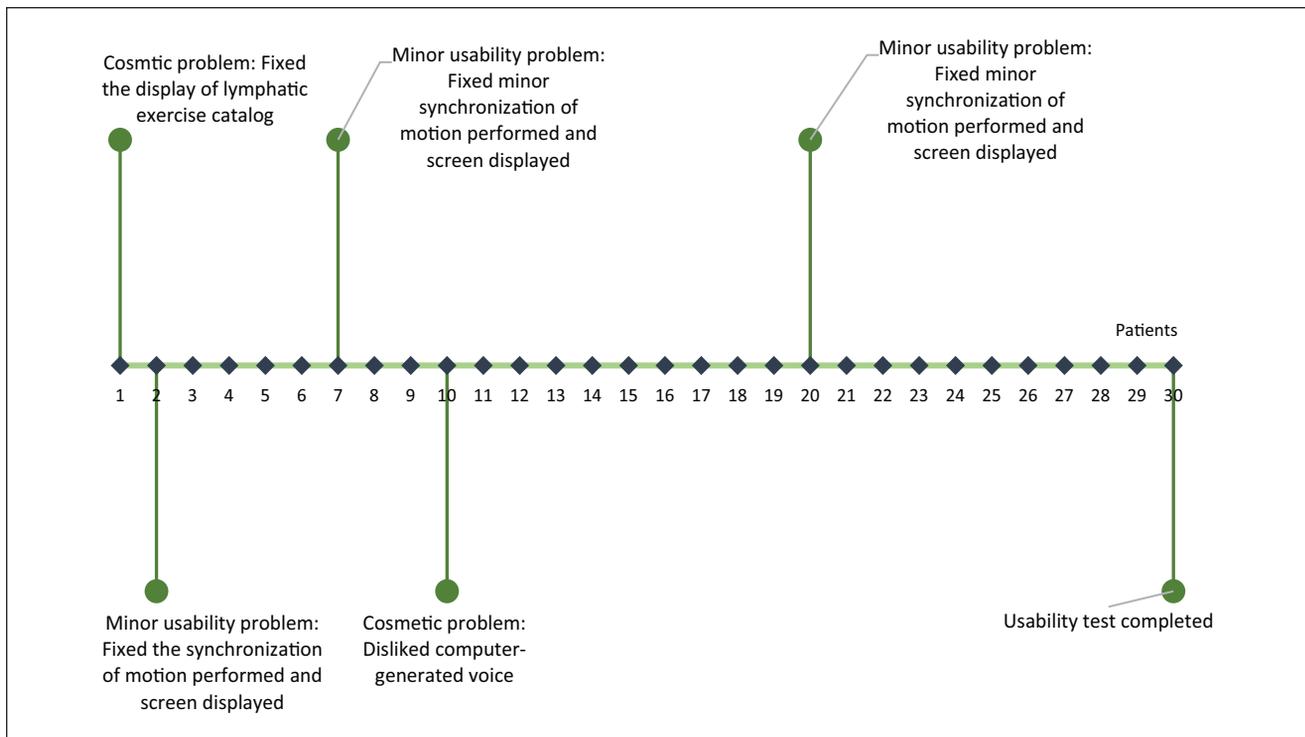


Figure 3. Refinement of the Kinect-enhanced lymphatic exercise training system.

lymph nodes procedure(s), and receipt of radiation and chemotherapy. Height and weight were measured and body mass index [BMI] calculated.

The Perceived Ease of Use and Usefulness Questionnaire is a valid and reliable 8-item instrument to evaluate users' acceptance of a new information system.^{19,28,29} Items were rated on a 5-point Likert Scale that ranged from 2 (strongly agree) to -2 (strongly disagree).¹⁹

The Post Study System Usability Questionnaire was used to assess user satisfaction with system usability on a Likert scale that ranged from 1 (strongly agree) to 7 (strongly disagree).³⁰ A modified 13-item tool that focused on the system's usefulness and information quality was used in the study.¹⁹ The questionnaire consists of 3 subscales, namely: system usefulness, information quality, and interface quality. The overall reliability of the scale was .97.^{19,30}

Breast Cancer and Lymphedema Symptom Experience Index (BCLE-SEI) was used to assess lymphatic pain (i.e., pain/aching/soreness), arm/hand swelling, total swelling (i.e., sum of arm/hand, breast, and chest wall swelling), and lymphedema symptom occurrence (i.e., number and severity of lymphedema symptoms), including impaired limb mobility in shoulder, arm, elbow, wrist, fingers, firmness, tightness, heaviness, fibrosis (toughness or thickness of skin), stiffness, tenderness, hotness/increased temperature, redness, blistering, numbness, burning, stabbing, tingling (pain

and needles), limb fatigue/weakness, and seroma (pocket of fluid developed).^{7-9,18,31} Adequate internal consistency was demonstrated with a Cronbach's alpha of .92 for symptom occurrence. Discriminant validity of the instrument was supported by a significant difference in symptom occurrence ($z = -6.938, P < .000$) between breast cancer survivors with and without lymphedema.^{18,31} The occurrence and severity of each of the 24 lymphedema symptom were evaluated. Symptom severity was rated on a Likert scale that ranged from "0" (absence of a symptom) to "4" (presence of a symptom). Higher scores indicate more severe symptoms. A response frame of "now" was used when rating each symptom before and after the intervention.

Lymph Fluid Level by Bioimpedance was assessed using the Imp XCA[®] (Impedimed, Brisbane, Australia), a bioelectrical impedance analysis (BIA) device before and after the intervention. The device measures the resistance of the extracellular fluid (i.e., the impedance) in terms of the L-Dex ratio, taking into consideration the ratio between the dominant and non-dominant arms.^{32,33} With accumulation of lymph fluid, the impedance of the limb decreases and the L-Dex ratio increases. The normal L-Dex ratio ranges from -10 to +10, equivalent to impedance ratios of .935 to 1.139 for the affected dominant arm and .862 to 1.066 for the non-affected non-dominant arm, respectively. A L-Dex ratio < -10 indicates a mistake in performing the measurement. A L-Dex ratio of ≥ 7.1 indicates

that a patient has an abnormal accumulation of lymph fluid or lymphedema; the higher L-Dex ratio indicates the greater severity of abnormal accumulation of lymph fluid or lymphedema.^{32,33}

Qualitative Data Collection At the completion of the trial, patients were asked to provide narrative responses to the open-ended questions, “what do you like about the system,” “what do you dislike about the system,” and “what can be improved?”

Data Analysis

Prior to statistical analyses, data were examined for accuracy and completeness. Kolmogorov-Smirnov test was used to identify whether the data fit a normal distribution. Descriptive statistics were used to summarize study variables, stratified by time-point of pre- and post- Kinect-TOLF intervention. Continuous variables were summarized in terms of means, medians, standard deviations (SD), ranges, and quantiles. Categorical variables were summarized using frequencies and proportions. Confidence intervals were reported to quantify the precision of estimates. The alpha level was set at .05 and 95% confidence intervals [CI] were reported for all of the statistical tests when appropriate. We used R version 3.6.2 for all of the statistical analyses.

For ordinal outcomes (i.e., lymphatic pain, hand/arm swelling) as well as for the continuous outcome of total swelling, Wilcoxon signed-rank tests were performed to test median differences in patients’ scores between pre- and post- Kinect-TOLF intervention. Spearman’s rank correlation coefficients (ρ_{Spearman}) were calculated to assess whether pre-intervention symptom levels were associated with symptom change scores for these outcomes. Effect sizes for each test were reported in the form of Wilcoxon’s r .

Changes in L-Dex values, the total number of symptoms and total symptom severity scores were estimated using a simple linear regression of the difference between the pre- and post-intervention values on the pre-intervention value (mean-centered).³⁴ For each linear model, diagnostic plots were evaluated to ensure statistical assumptions were met. The intercept in the model represents the mean difference in patient outcomes between the pre-intervention values and the slope. Significant intercept suggests a relationship between pre-intervention values and the amount of within-person change observed at post-intervention (e.g., patient with higher pre-intervention pain scores may experience a greater degree of relief at post-intervention than patients with lower pain scores at pre-intervention). We report Cohen’s d as an indicator of effect size for mean differences.

Qualitative data from the responses to the open-ended questions at the completion of the trial were summarized thematically.^{2,17-19} To ensure the credibility of qualitative

data analysis, we used a modified iterative 7-step descriptive data analysis method^{2,17-19} to examine data, compare codes, challenge interpretations, and inductively develop themes. First, the first author and other 2 authors read the qualitative data independently several times to gain a broad understanding of the text. Second, the 3 authors met as a group to identify key quotations and discuss key codes related to the study. Third, the 3 authors combined the coded quotations into 1 file and confirmed the accuracy of the codes and quotations. Fourth, the 3 authors carefully analyzed quotation files and identifying major themes by putting key coded quotations for each theme. Fifth, the 3 authors met as a group to review major themes together and engaged in active dialogue to resolve any discrepancies. Sixth, the 3 authors validated the structure of themes by reviewing the qualitative data. Finally, the authors conducted multiple discussions until consensus was achieved about the identified themes and each aspect of the process of data analysis. Efforts were made to differentiate and compare each theme with careful selection of quotations demonstrating the essence of the study experience.¹⁷⁻¹⁹

Results

Characteristics of the Patients

A total of 30 patients completed the feasibility clinical trial. No injury or safety issues occurred during the trial. The patients had a mean age of 61.7 years and a mean BMI of 28.4 kg/m². Among these patients, 86.7 % had a bachelor’s or graduate degree, 46.7% were married, 46.7% were employed, and 46.7% lived alone (Table 2).

As shown in Table 3, 43.3% of the patients had a lumpectomy, 60% had a mastectomy, 56.7% had breast reconstruction, 83.3% had chemotherapy, and 90% had radiation therapy. While 23.3% of the patients underwent axillary lymph node dissection, 30% had only sentinel lymph node biopsy. The mean number of lymph nodes removed was 11.4. Fifty percent of the patients were diagnosed with and treated for lymphedema. The mean years elapsed since the breast cancer diagnosis was 7.54 (SD=6.24; median=5.16, range=2-23 years). Among the 30 patients, 10 (33%) patients had a L-Dex ratio ≥ 7.1 and 20 (67%) patients had a L-Dex ratio < 7.1 .

Feasibility

Feasibility of the study was demonstrated by timely study accrual (N=30) in less than 3 months, ahead of the planned 6 months recruitment. The study achieved 100% protocol adherence with no patient withdrawal and protocol deviation. Of the 50 patients who were eligible for the study, only 8 patients declined the study without giving a reason. Twelve patients were eager but not able to

Table 2. Demographic Characteristics of Patients (N=30).

Age in years	Mean (standard deviation [SD]; range) 61.7 (9.77; 42-82)
Body mass index	Mean (standard deviation [SD]; range) 28.4 (6.3; 21.6-42.6)
Ethnicity	n (%)
White	15 (50)
Asian	5 (16.7)
Black or African-American	5 (16.7)
Hispanic	3 (10)
More than 1 race	2 (6.7)
Highest level of education	n (%)
Partial college/professional school degree	4 (13.3)
Bachelor's degree	17 (56.7)
Master's/doctoral degree	9 (30)
Marital status	n (%)
Married	14 (46.7)
Divorced/separated	6 (20)
Single, never married	10 (33.3)
Employment	n (%)
Working now	14 (46.7)
Retired	14 (46.7)
Looking for work, unemployed	2 (6.6)
Residence status	n (%)
Home-alone	14 (46.7)
Home-family	16 (53.3)
Financial status	n (%)
Comfortable: have more than enough to make ends meet	11 (36.7)
Have enough to make ends meet	18 (60)
Do not have enough to make ends meet	1 (3.3)
Smoking history	n (%)
Never smoked	22 (73.3)
Former (stopped more than 1 year before this encounter)	8 (26.7)
Drinking habits	n (%)
Never	4 (13.3)
Fewer than 1 drink per week	14 (46.7)
1 alcoholic drink per week	3 (10)
2-7 drinks per week	8 (26.7)
7 or more drinks per week	1 (3.3)

participate in the study due to unexpected family events, time conflicts, and long-distance travel.

Usability

Patients' responses to questions regarding Nielson's heuristic violations²³⁻²⁵ indicated no major usability problems or usability catastrophe associated with the Kinect-TOLF during the trial. Specifically, none of the 30 patients reported

Table 3. Clinical Characteristics of Patients (N=30).

Location of cancer	n (%)
Right breast	16 (53.3)
Left breast	14 (46.7)
Sentinel lymph nodes biopsy	n (%)
Yes	9 (30)
No	21 (70)
Axillary lymph nodes dissection (ALND)	n (%)
Yes	7 (23.3)
No	23 (76.7)
Sentinel lymph nodes biopsy and ALND	n (%)
Yes	15 (50)
No	15 (50)
Mastectomy	n (%)
Yes	18 (60)
No	12 (40)
Lumpectomy	n (%)
Yes	13 (43.3)
NO	17 (56.7)
Breast reconstruction	n (%)
Yes	17 (56.7)
No	13 (43.3)
Being diagnosed with lymphedema	n (%)
Yes	15 (50)
No	15 (50)
Lymph fluid level by bioimpedance	n (%)
L-Dex ratio <7.1	20 (67)
L-Dex ratio ≥7.1	10 (33)
Chemotherapy	n (%)
Yes	25 (83.3)
No	5 (16.7)
Radiation therapy	n (%)
Yes	27 (90)
No	3 (10)
Number of lymph nodes removed	Mean (standard deviation; range) 11.4 (9.1; 1 – 30)
Times since breast cancer diagnosis in years	Mean/median (standard deviation; range) 7.54/5.16 (6.24; 2–23)

major usability problems or usability catastrophes; 24 (80%) reported no usability problem; 4 (13.3%) reported minor usability problems (ie, minor mis-synchronization of the motion performed and what the screen displayed); and 2 (6.7%) reported cosmetic problem (ie, dislike the computer-generated voice and display of the catalog of the exercises). The heuristic evaluation demonstrated that the iterative process of refinement of the Kinect-TOLF was effective. By the last 10 participants, no usability problems were reported.

Acceptance

Table 4 presents detailed information about patients' responses to *The Perceived Ease of Use and Usefulness*

Table 4. The Perceived Ease of Use and Usefulness Questionnaire (N=30).

	Strongly agree n (%)	Agree n (%)	Neutral n (%)	Disagree n (%)	Strongly disagree n (%)
I find the system easy to use.	18 (60)	10 (33.3)	1 (3.3)	1 (3.3)	0 (0)
Learning to operate or follow the system is easy for me.	17 (56.7)	11 (36.7)	1 (3.3)	1 (3.3)	0 (0)
Interaction with the system is difficult.	1 (3.3)	2 (6.7)	1 (3.3)	13 (43.3)	13 (43.3)
I find it easy to get the system to do what I want it to do.	14 (46.7)	11 (36.7)	3 (10)	2 (6.7)	0 (0)
The system is flexible to interact with.	14 (46.7)	13 (43.3)	1 (3.3)	2 (6.7)	0 (0)
It is easy for me to remember how to perform tasks using the system.	14 (46.7)	12 (40)	3 (10)	1 (3.3)	0 (0)
Interacting with the system requires a lot of mental effort.	0 (0)	2 (6.7)	5 (16.7)	12 (40)	11 (36.7)
My interaction with the system is clear and understandable.	17 (56.7)	11 (36.7)	1 (3.3)	1 (3.3)	0 (0)

Table 5. The Post-Study System Usability Questionnaire (N=30).

Subscales	Items	Mean (SD) ^a	Median	Range ^b
System	Overall, I am satisfied with how easy it is to use this system.	1.4 (0.62)	1	1-3
Usefulness	It was simple to use this system.	1.53 (0.82)	1	1-4
	I could effectively follow the system to learn how to perform the lymphatic exercises.	1.23 (0.51)	1	1-3
	I felt comfortable using this system to learn how to perform the lymphatic exercises.	1.33 (0.96)	1	1-6
	It was easy to learn the lymphatic exercises using this system.	1.17 (0.46)	1	1-3
	I believe I could learn how to perform the lymphatic exercises correctly using this system.	1.37 (0.99)	1	1-6
Interface	The system gave error messages that clearly told me how to fix problems.	1.4 (0.81)	1	1-5
	Quality	Whenever I made a mistake in performing the lymphatic exercises, the system immediately told me so.	1.53 (0.82)	1
Information quality	The information (such as on-screen messages) provided with this system was clear.	1.23 (0.5)	1	1-3
	It was easy to follow the system to learn the correct way to perform the lymphatic exercises.	1.53 (1.07)	1	1-6
	The information provided for the system was easy to understand.	1.33 (0.55)	1	1-3
	The information was effective in helping me to learn to correctly perform the lymphatic exercises.	1.2 (0.48)	1	1-3
	The organization of information on the system screens was clear.	1.2 (0.5)	1	1-3

^aSD: Standard Deviation.

^bOn a scale of 1 to 7, 1 represents strongly agree and 7 represents strongly disagree.

Questionnaire.^{28,29} Over 90% of patients strongly agreed or agreed that the Kinect-TOLF was easy to learn, and flexible and easy to operate. Further, 93.4% of patients strongly agreed or agreed that their interactions with the system were clear and understandable. Over 80% of patients strongly agreed or agreed that the Kinect-TOLF made it easy for them to remember how to perform the lymphatic exercises. Table 5 shows patients' responses to the *Post Study System Usability Questionnaire*.³⁰ Average ratings on all of the items ranged from 1.20 to 1.53 on a scale that ranged from 1 (strongly agree) to 7 (strongly disagree), indicating that participants strongly agreed or agreed on user satisfaction with the Kinect-TOLF.

Effects of the Kinect-TOLF on Lymphatic Pain, Swelling, and Lymphedema Symptoms

Lymphatic pain and swelling. Table 6 provides the results of effects of the Kinect-TOLF on lymphatic pain, swelling,

and lymphedema symptoms. Significant reductions were found in lymphatic pain ($Med\Delta = -1.00$, $CI = [-1.5, -0.1]$, $P = .004$), arm/hand swelling ($Med\Delta = -1.00$, $CI = [-1.5, -0.5]$, $P = .004$), and total swelling scores ($Med\Delta = -1.5$, $CI = [-2.0, -1.0]$, $P = .003$) scores. Spearman's rank correlation coefficients suggest that patients with higher pain scores at the pre-intervention assessment had significantly greater decrease in pain ($\rho_{Spearman} = .49$, $P = .006$). Patients with greater severity of arm/hand swelling at the pre-intervention assessment had a significantly greater reduction in arm/hand swelling ($\rho_{Spearman} = .66$, $P < .0001$). Greater severity of total swelling at pre-intervention assessment was associated with greater improvement ($\rho_{Spearman} = .36$, $P = .048$).

Lymphedema symptom occurrence and severity. Table 7 presents the occurrence of the 24 lymphedema symptoms before and after the Kinect-TOLF intervention. Significant reductions were found in the total number of lymphedema

Table 6. Lymphatic Pain, Arm/Hand Swelling, Total Swelling, L-Dex, and Symptom Occurrence and Severity.

Outcome variables	Pre Kinect-TOLF			Post Kinect-TOLF			Change scores (post-pre differences)			
	Med	IQR	Range	Med	IQR	Range	Med difference (95%CI)	Statistics	P	Effect Size (95%CI)
Lymphatic limb pain	1	1	0-4	0	2	0-3	-1.0 (-1.5, -0.1)	-2.91 ^a	.004	0.53 (0.25, 0.74)
Arm/hand swelling	1	2	0-4	0	1	0-3	-1.0 (-1.5, -0.5)	-2.92 ^a	.004	0.54 (0.28, 0.71)
Total swelling	2	1.75	0-8	1	2	0-9	-1.5 (-2.0, -1.0)	-2.96 ^a	.003	0.54 (0.26, 0.76)
L-Dex	12.4	25.4	-7.2 to 108.1	9.7	24.6	-9.3 to 106.0	-2.7 (-4.7, -0.7)	-2.76 ^b	.010	0.50 ^d (0.11, 0.89)
Number of symptoms	10.5	5.6	1-19	6.4	6.6	0-22	-3.8 (-5.5, -2.1)	-4.56 ^b	<.001	0.85 ^d (0.43, 1.29)
Symptom severity score	19.3	15.5	2-66	12.4	16.8	0-66	-5.3 (-9.5, -1.1)	-2.58 ^b	.016	0.49 ^d (0.11, 0.88)

Abbreviation: Med, median; IQR, inter-quartile range; SD, standard deviation.

^aWilcoxon signed-rank test Z-Statistic.

^bPaired t-test t-statistic.

^cWilcoxon's *r*.

^dCohen's *d*.

Table 7. Lymphedema Symptom Occurrence Pre- and Post- Kinect-TOLF Intervention.

Symptoms	Pre-Kinect-TOLF	Post-Kinect-TOLF
	n (%)	n (%)
Lymphatic pain (ie, pain/aching/soreness in the affected limb or body side)	24 (80.0)	12 (40.0)
Arm/hand swelling	21 (70.0)	14 (46.67)
Breast swelling	11 (36.7)	7 (23.3)
Chest wall swelling	9 (30.0)	5 (16.7)
Limited movement in the affected shoulder	15 (50.0)	12 (40.0)
Limited movement in the affected elbow	8 (26.7)	6 (20)
Limited movement in the affected wrist	6 (20.0)	7 (23.3)
Limited movement in the affected fingers	11 (36.7)	7 (23.3)
Limited movement in the affected arm	21 (70.0)	13 (43.3)
Arm firmness	21 (70.0)	8 (26.7)
Arm tightness	24 (80.0)	16 (53.3)
Arm heaviness	21 (70.0)	13 (43.3)
Fibrosis (ie, toughness or thickness of skin in the affected limb)	9 (30.0)	7 (23.3)
Stiffness in the affected limb	21 (70.0)	13 (43.3)
Tenderness in the affected limb	17 (56.7)	7 (23.3)
Hotness/increased temperature in the affected limb	7 (23.3)	3 (10.0)
Redness in the affected limb	2 (6.7)	2 (6.7)
Blistering in the affected limb	1 (3.3)	1 (3.3)
Numbness in the affected limb	15 (50.0)	12 (40.0)
Burning in the affected limb	5 (16.7)	3 (10.0)
Stabbing in the affected limb	6 (20.0)	4 (13.3)
Tingling (pins and needles) in the affected limb	15 (50.0)	9 (30.0)
Limb fatigue or weakness	18 (60.0)	14 (46.7)
Seroma (pocket of fluid developed)	7 (23.3)	4 (13.3)

symptoms ($M\Delta = -3.8$, $CI = [-5.5, -2.1]$, $P < .001$) and total symptom severity scores ($M\Delta = -5.3$, $CI = [-9.5, -1.1]$, $P = .016$, Table 6).

Lymph fluid level by bioimpedance. A significant reduction in lymph fluid levels was found based on mean L-Dex scores ($M\Delta = -2.68$, $CI = [-4.67, -0.69]$, $P = .010$). Higher reductions in mean L-Dex scores were observed in the 10

patients who had abnormal lymph fluid level (ie, L-Dex of ≥ 7.1) at pre-intervention assessment ($M\Delta = -5.19$, $CI = [-1.75, -8.63]$, $P = .008$).

Qualitative Results

Five main themes emerged from the qualitative data, namely: standardized learning for lymphatic exercises;

Table 8. Themes and Representative Quotes from Qualitative Evaluation (N=30).

Providing a standardized format for lymphatic exercises	<ul style="list-style-type: none"> • “The model is easy to follow & gives a standardized format for proper maneuvers.” • “It is very helpful in ensuring one does the exercises properly. Additionally, the feedback is very helpful.”
Having a control over the training	<ul style="list-style-type: none"> • “I had control over the exercises and could repeat them if I did not perform them well.” • “Ability to follow along independently.”
Effectiveness of training	<ul style="list-style-type: none"> • “It really clearly showed me how to do the exercises and where I was making errors.” • “The exercises were thoroughly explained: Not only the how but the why. The feedback was immediate so you can clearly tell if you were doing them correctly.” • “I like the fact that it tells you if you are doing the exercises correctly.” • “I like the correction when I do the exercise. Now, I know how to do this correctly.” • “It really help me to adjust into correct position of my shoulder (a difficult task for me).” • “It is very helpful in ensuring one does the exercises properly. Additionally, the feedback is very helpful.” • “Step by step instructions on each exercise and its immediate feedback.” • “Exercises were clearly explained. Illustrations also clear. Immediate feedback helpful.” • “The interaction with the model and viewing my own body at the same time was fun.” • “I like everything about it, I think the system as a whole is quite perfunctory. I think it is a well-designed system for someone living with lymphedema such as me.”
Effectiveness of the lymphatic exercises	<ul style="list-style-type: none"> • “I think it’s great and effective. I can feel the positive difference within minutes of doing the exercises.” • “I am more than satisfied because the movements help me to stretch out tightness and relieve pain.” • “I like it. For breast cancer survivors, we can follow the program and see the videos that are easy to follow with no problem. Good for practicing exercises.” • “The exercises are very helpful.” • “Useful exercises.”
Ease of use	<ul style="list-style-type: none"> • “It is good and easy to follow and I like it that is shows how you are breathing etc.” • “Easy to use and immediate feedback was given.” • “It was easy to follow.” • “I like everything, it was pretty straightforward.”

having a control over the training; effectiveness of the training; effectiveness of the lymphatic exercises; and easy to use. Table 8 provides representative quotes for each of the theme.

The most salient theme was that patients felt that the Kinect-TOLF was effective in teaching them how to do the lymphatic exercises correctly by providing them with a standardized format for each exercise that was “easy to follow.” Patients appreciated that the Kinect-TOLF provided immediate feedback on “where [they were] making errors.” As 1 patient remarked, the Kinect-TOLF helped her to adjust her shoulder to the correct position for the exercises, which is a “difficult task for me.” Patients noted that the Kinect-TOLF increased their sense of self-efficacy because the program allowed them to learn and perform the exercises independently and that they could repeat them as often as they wanted to do so. Patients felt that the lymphatic exercises had immediate effects to “stretch out tightness and relieve pain,” and have a “positive difference within minutes of doing the exercises.” Finally, patients concluded that the Kinect-TOLF was “easy to use” and “straightforward.”

Discussion

The efficacy of self-care exercise interventions relies on accurate body movements. Findings from this study demonstrated that the Kinect-TOLF intervention is feasible and efficacious in training patients to perform lymphatic exercises accurately. Feasibility of the study was supported by 100% of study accrual ahead of time (i.e., more than 3 months ahead of the planned 6 months of recruitment) and 100% of protocol adherence without any protocol deviation and patient withdrawal from the study. The majority of our patients reported no usability problems and agreed that the system was easy to learn and operate, flexible to use, clear, and understandable. As expected, some patients reported that it took a lot of mental effort to learn the lymphatic exercises. However, over 80% of them indicated that the Kinect-TOLF made it easy for them to remember how to correctly perform the exercises. Nearly every patient expressed how much they appreciated the real-time feedback, which enabled them to perform each exercise correctly. Overall, our findings provide preliminary evidence that the Kinect-TOLF is a simple and efficacious system that patients can use to learn self-care therapeutic exercises correctly.

The goal of the TOLF lymphatic exercises is to relieve lymphatic pain, swelling, and lymphedema symptoms.^{17,18} In face-to-face¹⁷ and avatar-based coaching¹⁸ studies, the TOLF intervention was safe, feasible, and efficacious in relieving lymphatic pain and reducing lymphedema symptoms as well as in decreasing the risk of objective lymph fluid accumulation by limb volume using infrared perometer. The current study extends these findings and suggests that the Kinect-TOLF is safe, feasible, and have immediate effects on lymphatic pain, swelling, lymphedema symptoms, and lymph fluid level after a single training session of the Kinect-TOLF. Significant reductions were found in lymphatic pain ($P=.004$), arm/hand swelling ($P=.004$), total swelling ($P=.003$), number of lymphedema symptoms ($P<.001$), and symptom severity scores ($P=.016$). In addition, patients who had the greatest severity of lymphatic pain, arm/hand swelling, and total swelling prior to intervention had the greatest improvements in these symptoms. Taken together, these findings suggest that the effects of a single session of Kinect-TOLF intervention were immediate to relieve lymphatic pain, arm/hand swelling, total swelling, and lymphedema symptoms. Patients' immediate therapeutic responses are also supported by the qualitative data. Patients reported positive effects within minutes of performing the lymphatic exercises. These perceptions of immediate effects of the Kinect-TOLF are important because sustained behavior change is more easily maintained if patients perceive that an intervention is effective and easy to integrate into their daily lives.³⁵

The TOLF lymphatic exercises were designed to decrease lymph fluid levels.^{17,18} In a previous study,¹⁷ 97% of the 134 patients who received the face-to-face TOLF intervention maintained or decreased their preoperative limb volumes assessed using an infrared perometer at 12 months after surgery. In the current study, all of the patients had significant reductions in lymph fluid levels assessed using bioimpedance immediately after a single training session of Kinect-TOLF. In addition, greater reductions in lymph fluid levels were found in patients with abnormal lymph fluid levels (i.e., their scores decreased by 5.1 points). Given these results, it is reasonable to hypothesize that daily or weekly use of the Kinect-TOLF intervention may help patients to achieve normal lymph fluid levels.

Efforts to Prevent Bias

To prevent recruitment bias, patients were recruited from among the consecutively-identified breast cancer patients who reported persistent lymphatic pain or lymphedema symptoms in the ipsilateral upper limb or body at least 12 weeks after breast cancer surgery during routine clinical visit. In addition, the technology-enhanced Kinect-TOLF system ensured the fidelity of intervention delivery.

Strengths and Limitations of the Study

The strengths of this trial include the use of a well-designed Kinect-enhanced training system²⁰⁻²² based on an evidence-based effective intervention;¹⁷⁻¹⁹ an adequate sample size for feasibility^{26,27} and usability testing;^{23,24} and the use of both objective and subjective measures for efficacy testing. While not a randomized trial, this study provides an effect size for each outcome variable for future trials. As Kinect-TOLF lymphatic exercises can be used alone or as an adjunct therapy to current lymphedema treatment (e.g., compression therapy, manual lymph drainage, or other forms of exercises), a randomized clinical trial with a larger sample is warranted to confirm the unique or synergistic efficacy of the Kinect-TOLF in comparison to current lymphedema treatment and other forms of exercises or movement therapy. Future studies should also consider what constitutes a clinically meaningful difference in using the Kinect-TOLF to reduce lymphatic pain, swelling, lymphedema symptoms, and decrease lymph fluid levels. In terms of limitations, patients were highly educated and had familiarity with computers and mobile devices.

Conclusion

The Kinect-TOLF is an easy-to-use, low-cost intervention that enables patients to perform the therapeutic lymphatic exercises in a standardized way. This intelligent Kinect-enhanced lymphatic exercise intervention enhances intervention fidelity and insures that each patient receives the same quality of intervention. Importantly, findings from this study suggest that a single session of Kinect-TOLF intervention immediately reduces lymphatic pain, swelling, and lymphedema symptoms, as well as decreases lymph fluid levels. The findings of this study should be further evaluated in a large randomized clinical trial. If the results are replicated, the Kinect-TOLF intervention will be relatively easy to implement in clinical practice or at home to relieve lymphatic pain, swelling, and lymphedema symptoms, as well as to decrease lymph fluid level, ultimately to improve the QOL of breast cancer survivors.

Acknowledgments

We thank Ms. Alejandra Yancey for helping manage the trial and data collection. We thank all the patients who participated in the trial. We thank nurses, physicians, and staff at NYU Perlmutter Cancer Center for their support of the trial.

Author Contributions

The "Author Contributions" section should be completed as follow: (1) Conception and design: Mei R. Fu, Yao Wang; (2) Administrative support: Mei R. Fu, Yao Wang, Deborah Axelrod, Amber A. Guth, Zhipeng Fan; (3) Provision of study material or patients: Mei R. Fu, Deborah Axelrod, Amber A. Guth; (4) Collection and assembly of data: Mei R. Fu, Eunjung Ko, Simay

Yazicioglu, Jeanna M. Qiu, Anna Sang; (5) Data analysis and interpretation: Mei R. Fu, Melissa McTernan, Jeanna M. Qiu; (6) Manuscript Drafting: Mei R Fu, Jeanna M. Qiu, and Melissa McTernan; (7) Manuscript revision and editing: All authors. (8) Final approval of manuscript: All authors.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was supported by the National Institute of Health /National Science Foundation /National Cancer Institute (1R01CA214085-01) with Mei R Fu and Yao Wang as the multiple principal investigators. This study was also supported by a research grant from Judges and Lawyers Breast Cancer Alert with Mei R Fu as the principal investigator. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the funders. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Human and Animal Rights and Informed Consent

This study (IRB # (S19-00222) was approved by the Institutional Review Board of a metropolitan cancer center in New York of the United States. All the human participants signed the informed consent. This study does not contain any animal subjects.

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