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Examining upper limb kinematics and dysfunction of breast cancer survivors in functional dynamic tasks

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A R T I C L E I N F O

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A B S T R A C T

Background: Comorbidities within the breast cancer population can reduce quality of life. Current breast cancer survivor upper limb kinematic strategies unfortunately lack robust connection with performing important activities of daily living.

Methods: Accordingly, fifty breast cancer survivors performed 88 dynamic tasks (divided into range of motion-reach, range of motion-rotate, activity of daily living, and work tasks). Humerothoracic and scapulothoracic angles were extracted from motion capture data. Bilateral differences existed for range of motion, and maximal and minimal scapulothoracic and humerothoracic angles.

Findings: Generally, the affected side used less range of motion across task types. Humerothoracic angles on the affected side experienced 6.7° less range of motion in plane of elevation in range of motion-reach ($p < 0.01$), 2.3° less elevation angle range of motion in range of motion-rotate ($p = 0.01$), and 7.1° more internal rotation range of motion in range of motion-rotate ($p < 0.01$). Scapulothoracic angles on the affected side had 2° more anterior/posterior tilt range of motion in work tasks ($p = 0.03$), 3.4° less maximal protraction in activity of daily living tasks ($p = 0.01$), and 3.5° less minimum downward rotation in range of motion-rotate ($p < 0.01$).

Interpretation: A reduced range of motion on the affected side suggests the breast cancer population had less varied movement strategies, keeping movements in narrower ranges to avoid disability, pain, or subacromial impingement. This investigation produced an unprecedentedly diverse collection of three-dimensional humerothoracic and scapulothoracic kinematics for a breast cancer population. Documentation of physical capability, dysfunction, and adaptive strategies is a crucial step towards developing targeted strategies for enhancing functional recovery in breast cancer survivors.

1. Introduction

Breast cancer is the most common cancer among females in Canada. Breast cancer constitutes 25.9% of new cancer cases each year for females, and 1 in 9 Canadian females will be diagnosed in their lifetime (CCS, 2015). Continued research on breast cancer population (BCP) prevention and care has produced positive results, and 5-year survivorship has reached ~90% in women aged 40–79 (CCS, 2015). Patients typically undergo surgical treatments, with adjuvant therapy following surgery to ensure removal of the cancerous cells. Mastectomies continue to be the most common surgical treatment, representing 45% of total surgical procedures, followed by breast conserving treatment and axillary node dissection in more advanced tumours (Courneya et al., 2002; Markes et al., 2006; Nemoto et al., 1980). Radical mastectomies are the most effective surgical treatment with only a 4.4% relapse rate (van der Sangen et al., 2011), but involve removal of the breast tissue, overlying skin, pectoralis muscle and extensive lymph node dissection (Dalberg et al., 2010). Improvements in imaging have led to increased popularity of modified radical mastectomies, which involve the removal of pectoral fascia, but leave the muscle intact (Dalberg et al., 2010).

This removal of muscle and tissue from surgery and adjuvant treatment generates a substantial volume and range of comorbidities. Range of motion (ROM) defects and/or lymphedema complications exists in 4 out of 5 patients receiving radical mastectomies (Sugden et al., 1998). While modified radical mastectomies reduce lymphedema risk and improves range of motion compared to radical mastectomies, 35% of patients still had range of motion restriction in one or more directions (Lauridsen et al., 2008). Across the BCP, treatment-related sequelae affects 30–82% of patients, and commonly include reduced range of motion, weakness, pain, numbness and swelling (Kwan et al., 2002; Lauridsen et al., 2008; Maycock et al., 1998; Rietman et al.,

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Fig. 1. Motion capture setup. Motion capture markers were placed over bony landmarks of the torso and upper extremity, with acromion clusters placed directly over the flat part of the acromion.

2004). The duration of these side effects vary across symptoms and between individuals, and can last from days to years (Schmitz et al., 2010). These upper limb morbidities can limit or interfere with activities of daily living (ADL), negatively affecting return to work and quality of life (Markes et al., 2006; Rietman et al., 2003).

Detailed knowledge surrounding upper limb functional ability of the BCP is limited. Accurate documentation of upper limb morbidity in the BCP is rare, and relationships between impairments, disability, task performance and quality of life are scarce (Rietman et al., 2003, 2004; Thompson et al., 1995). Various fundamental shoulder movements appear to be affected differentially, exacerbating the problem. Mean restrictions in abduction and forward flexion compared to the unaffected side have been reported at 21° and 12°, respectively (Kuehn et al., 2000), while other research quantified decreases in range of motion from 1 to 67° (Lee et al., 2008). Treatment strategy affects outcomes, with mastectomy patients reporting reduction in arm function more often (77%) than those with breast conserving therapy (33–39%), and reductions in flexion, abduction and external rotation more prominent in those who received mastectomies (Ebaugh et al., 2011; Harrington et al., 2013; Lauridsen et al., 2008; Nesvold et al., 2008; Sugden et al., 1998). Ability in these fundamental motions may not correlate effectively to motions of activities of daily living, and assessments of the BCP performing these tasks are incomplete. Systematic BCP evaluation is critical, as specific and effective preventative and treatment strategies do not exist to promote return to function and work. A prerequisite for creating these treatment strategies is rigorous quantification of the physical capabilities typical within the BCP for practical activities. This study describes the upper limb capacities and dysfunctions in female breast cancer survivors in terms of scapulothoracic and humerothoracic kinematics during range of motion, activities of daily living and simulated work activities. We hypothesize that the BCP have reduced humeral angle of elevation and external rotation ranges of motion, but increased scapular protraction on the affected side compared to the contralateral limb.

2. Methods

Anthropometrics and a brief medical history were recorded for 50 breast cancer survivors, who then performed 88 dynamic functional tasks during which motion capture was recorded.

2.1. Participants

Participants included 50 female breast cancer survivors (59.4 (SD 9.7) years, range 31–83 years; stature 1.7 (SD 0.1) m, range 1.5–1.8 m; body mass 71.7 (SD 11.8) kg, range 51.4–97.7 kg) who were previously diagnosed with stages I, II or III unilateral breast cancer. Participants had completed cancer therapies including surgery, radiation and/or chemotherapy at least 3 months prior to participation, and were predominantly right handed (n = 47). Cancer was on the left breast for 27 participants. Twenty-seven participants had mastectomies (16 prophylactic bilateral); 34 had lumpectomies and 48 had axial node dissection surgeries. Thirty-four participants received hormone replacement therapy, 34 had received chemotherapy and 37 had received radiation treatments. The average time since diagnosis was 74.9 (SD 59.6) months; range 12–228 months. All participants provided informed consent prior to data collection, and this study received ethics clearance through the institutional Office of Research Ethics.

2.2. Instrumentation

Motion capture was collected for both arms and the torso during each of the dynamic tasks. Three-dimensional motion was tracked using an 8-camera Vicon MX20 system (Vicon, Oxford, UK). Individual markers were placed over palpable anatomical landmarks: bilaterally over the radial and ulnar styloids, medial and lateral epicondyles and acromion, as well as the suprasternal notch, xiphoid process, and spinous processes of C7 and T8. Additional marker clusters were secured to rigid plates positioned on the upper arm and over the acromion (Fig. 1). The acromial marker cluster was placed over the flat part of the posterior-lateral acromion, just medial to the origin of the deltoid when

Table 1
Functional tasks performed by the breast cancer population during experimental protocol. All tasks were performed separately for left and right arms, except where marked by an asterisk (*) to indicate the task was performed bilaterally. Tasks were divided into 4 groups. All tasks (except for the standing lift) were performed seated in 43 cm high backless chair behind a 66 cm high table.

Task group	Task name	Description
ROM – reach tasks	Humeral flexion	Participants are instructed to elevate their arm anteriorly in the sagittal plane (elbow extended) to full range. Start/End position was arm at side.
	Humeral extension	Participants are instructed to elevate their arm posteriorly in the sagittal plane (elbow extended) to full range. Start/End position was arm at side.
	Humeral abduction	Participants are instructed to elevate their arm in the frontal plane (elbow extended) to full range. Start/End position was arm at side.
	Scaption	Participants are instructed to elevate their arm (elbow extended) in the scapular plane (30° anterior to the frontal plane) to full range. Start/End position was arm at side.
ROM – rotation tasks	Humeral IR at 45° elevation	With the elbow flexed to 90° and arm abducted to 45°, participants are instructed to internally rotate their humerus to full range.
	Humeral ER at 45° elevation	With the elbow flexed to 90° and arm abducted to 45°, participants are instructed to externally rotate their humerus to full range.
	Neutral scapular orientation*	Participants are instructed to identify the most comfortable neutral scapular posture while actively protracting and retracting the scapula (Smith et al., 2002). Start/End position was with hands resting on table in front of them.
	Scapular protraction*	Participants are instructed to protract the scapula (move the scapula in an anterior-lateral direction, moving the scapular border away from the vertebral column) (Solem-Bertoft and Wresterberg, 1993). Start/End position was with hands resting on table in front of them.
	Scapular retraction*	Participants are instructed to retract the scapula (move the scapula in a posterior-medial direction, moving the scapular border towards the vertebral column) (Solem-Bertoft and Wresterberg, 1993). Start/End position was with hands resting on table in front of them.
	Winging Scapula Test	Flex humerus to 30° against inferiorly-directed resistance.
ADL tasks	Comb hair	Participant combs the right, center and left side of the head once.
	Anterior reach to contralateral scapula	Participant reaches across chest and over opposite shoulder to wash contralateral scapula.
	Posterior reach to contralateral scapula	Participant reaches behind back and up to contralateral scapula.
	Wash opposite axilla	Participant reaches across chest to wash contralateral axilla.
	Eat with spoon	Participant brings a spoon to the mouth.
	Perineal care	Participant reaches behind back and places hand on sacrum.
	Posterior bra unfasten	Participant is instructed to simulate unfastening a bra at the spine height of the inferior angle of the scapula.
WORK tasks	Seated reach above shoulder (no load)	Participant reaches towards a target which is 1.5 m vertical from the ground and centered in front of the participant's body. [Task simulates reaching up to a shelf.]
	Seated reach above shoulder (1 kg load)	Participant reaches towards a target which is 1.5 m vertical from the ground and centered in front of the participant's body with a 1 kg load. [Task simulates reaching up to a shelf.]
	Seated reach above shoulder – scaled to torso-reach height with (no load)	Prior to collection, the researcher measures the 'torso-reach' distance, defined as the distance from participant's greater trochanter of the hip to the tip of the fingers when the arm is raised vertically. A target is placed in front (center) of the participant at a height of 80% of torso-reach distance plus the height of the chair. The participant reaches towards the target. [Task simulates reaching up to a shelf.]
	Seated reach above shoulder – scaled to torso-reach height (1 kg load)	Prior to collection, the researcher measures the 'torso-reach' distance, defined as the distance from participant's greater trochanter of the hip to the tip of the fingers when the arm is raised vertically. A target is placed in front (center) of the participant at a height of 80% of torso-reach distance plus the height of the chair. The participant reaches towards the target with a 1 kg load. [Task simulates reaching up to a shelf.]
	Seated side reach at shoulder height (no load)	Participant reaches out to side (in frontal plane) at shoulder height with extended arm.
	Seated side reach at shoulder height (1 kg load)	Participant reaches out to side (in frontal plane) at shoulder height with extended arm with 1 kg load.
	Standing 2-handed lift (4 kg load)*	Participant (standing) reaches for 4 kg load placed on floor in front of them. Participant lifts load and places it on table in front of them. [Simulates lifting a load equivalent to a 4 L milk bag.]

the shoulder was abducted 90° as per previous literature (Karduna et al., 2001; Ludewig and Cook, 2000; van Andel et al., 2009). A static calibration frame was taken before experimental testing and was used to establish the relationship between rigid clusters and calibration markers over anatomical landmarks. Six additional static calibration frames were taken with the a marker stylus tip palpating each of the three scapula anatomical landmarks (acromial angle, trigonum spinae and inferior angle) on both left and right sides. This data was used to calculate joint centers and segment coordinate systems were constructed using ISB recommendations (Wu et al., 2005). Kinematics were sampled at 50 Hz using Vicon Nexus 1.2 software (Oxford, UK).

2.3. Experimental protocol

Motion capture was recorded as participants performed 88 tasks (2 sets of 20 unilateral tasks on each arm and 2 sets of 4 bilateral tasks). These tasks included 10 tasks of shoulder ROM (as a measure of full ROM capacity), 7 ADL tasks (involving personal body care activities) and 7 work tasks (reaching tasks with and without loads) (Table 1). These tasks were similar to those previously investigated within healthy and elderly populations (Hall et al., 2011; Magermans et al., 2005; Murray and Jonson, 2004). Participants were provided up to 6 s to complete each task and were asked to perform each task as naturally as possible.

2.4. Data analysis

Kinematic analysis consisted of data filtering, marker reconstruction and local joint system construction, followed by conversion of marker data to joint centers and Euler decomposition. Static calibration trials were completed prior to experimental trials, allowing reconstruction in subsequent frames. All raw kinematic data were low-pass filtered with a frequency of 4 Hz, and local coordinate systems were defined using ISB standards (Wu et al., 2005). For the left side, directions were reversed to maintain the Z axis pointing to the right, the Y axis pointing superiorly and the X axis pointing anteriorly. The global coordinates of the left and right scapula landmarks (acromion angle, inferior scapular angle, root of the scapular spine) were identified using the position of the digitizing stylus tip in each of the six calibration tests (one calibration per digitized landmark). Static calibration tests determined the position of the scapular landmarks relative to the acromial cluster, and the humeral landmarks relative to the humeral cluster, and these were used to generate virtual scapular and humeral landmarks during dynamic tests. Scapulothoracic and humerothoracic joint descriptions were based on the Euler YXZ and YXY′ rotation sequences, respectively, as recommended by the ISB (Wu et al., 2005). The scapulothoracic rotations for both left and right sides were described as +upward/−downward rotation (β, about the X axis), +anterior/−posterior tilt (α, about the Z axis), and + retraction/−protraction (γ, about the Y axis). Scapular kinematics were reported as absolute values with respect to the local coordinate systems (the neutral "zero" position was defined as the alignment of the local coordinate systems of the scapula and the thorax). The humerothoracic rotations were described as magnitude of elevation (β, about the X axis or in layman terms degree of upward elevation of the upper arm raising), plane of elevation (γ, about the Y axis or in layman terms in which plane of forward flexion, backwards extension or laterally the arm was raised), and humeral rotation ($\gamma 2$, about the Y axis or in layman terms internal (towards midline) or external (away from midline) rotation of the upper arm). For both left and right sides, elevation was positive, plane of elevation was described as −90° in forward flexion and 0° in abduction, and humeral ER was positive and IR was negative (Fig. 2).

2.5. Statistical analysis

Statistical testing focused on quantifying differences in range of motion of humerothoracic and scapulothoracic angles between affected and unaffected sides. The maximal and minimal angles achieved during each functional task were determined, and averaged for each of the 2 sets of repeated tasks. Range of motion (minimal subtracted from maximal angle) was reported, similar to Hall et al. (2011). For range of motion, maximal and mineral humerothoracic and scapulothoracic angles, four repeated measures ANOVAs were completed within task type (ROM-Reach, ROM-Rotation, ADL or work task). All statistical analyses were completed using JMP 10.0 software (SAS Institute, North Carolina, USA). Statistical significance was set at $\alpha = 0.05$ for all tests. Post-hoc analysis was used to identify level differences ($p < 0.05$) between sides as required.

3. Results

Differences between affected and unaffected side existed for range of motion, as well as maximal and minimal scapulothoracic and humerothoracic angles. Generally, the affected side used less range of motion than the unaffected side. The results have been divided into humerothoracic and scapulothoracic sections below. Due to an irrecoverable software issue, all kinematic data was lost for one subject (both sides), and due to an unrelated wrist injury on the unaffected side, kinematics were collected for only the affected side for one other subject, which precluded their inclusion.

3.1. Humerothoracic kinematics

Differences existed between affected and unaffected humerothoracic ROM, maximal and minimal angle for some tasks. The affected side had reduced ROM in the plane of elevation (32.3° vs. 39.0°, $p = 0.0034$) in ROM-Reach tasks, as well as in elevation angle and plane of elevation in ROM-Rotate tasks (9.7° vs. 12.0°, $p = 0.0121$; and 15.3° vs. 18.6°, $p = 0.0440$). Additionally, the affected side was observed to have increased humeral rotation ROM in ROM-Rotate tasks and elevation in work tasks (33.6° vs. 26.5°, $p = 0.0036$ and 56.5° vs. 51.2°, $p = 0.0037$, respectively). In maximal humerothoracic angles, the affected side demonstrated reduced angles of elevation (48.4° vs. 54.9°, $p < 0.0001$) and a more anterior plane of elevation relative to the abduction plane (−21.1° vs. −17.2°, $p = 0.0449$), as well as less external rotation during work tasks (0.4° vs. 9.3°, $p = 0.008$). Minimum elevation angle was smaller for the affected side in ROM-Reach (29.5° vs. 35.2°, $p = 0.0001$), ROM-Rotate (38.5° vs. 42.7°, $p < 0.0001$) and ADL tasks (35.1° vs. 39.0°, $p = 0.0003$), and internal rotation was greater in ROM-Rotate (−26.5° vs. −8.6°, $p = 0.0124$), ADL (−69.5°

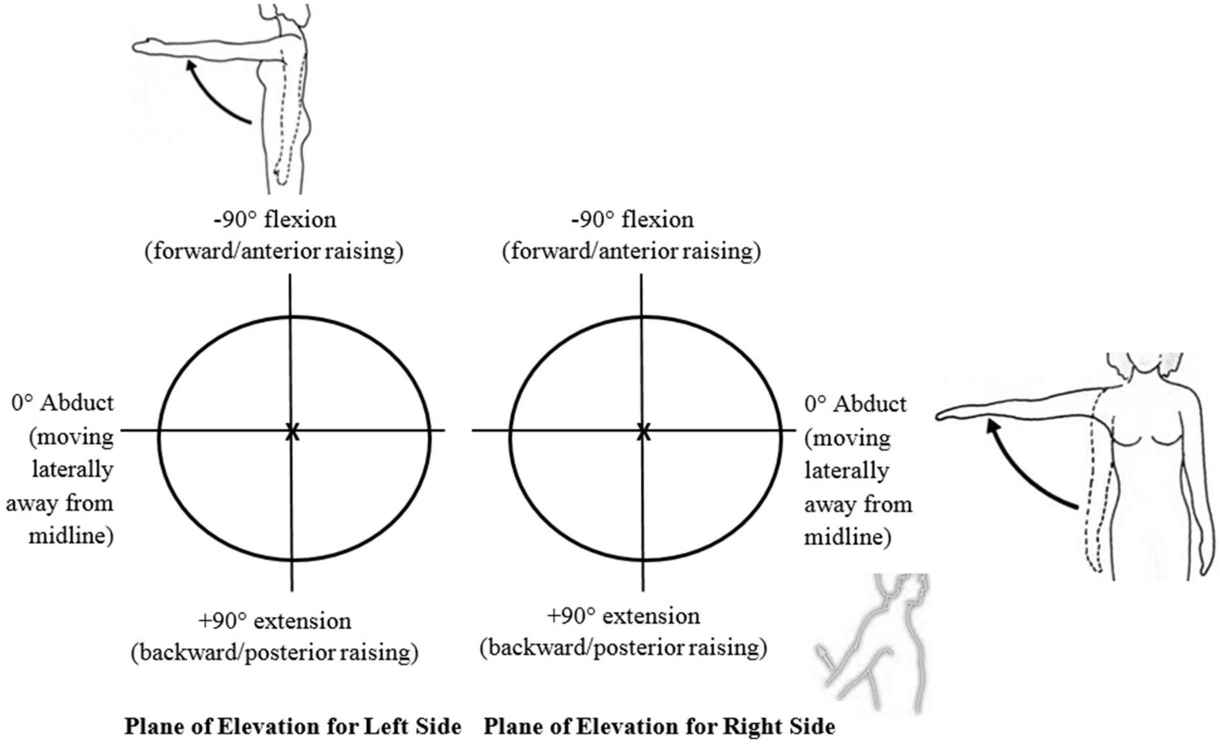

Fig. 2. Humerothoracic plane of elevation for left and right sides. Abduction represents a plane of elevation of 0° and forward flexion is −90°.

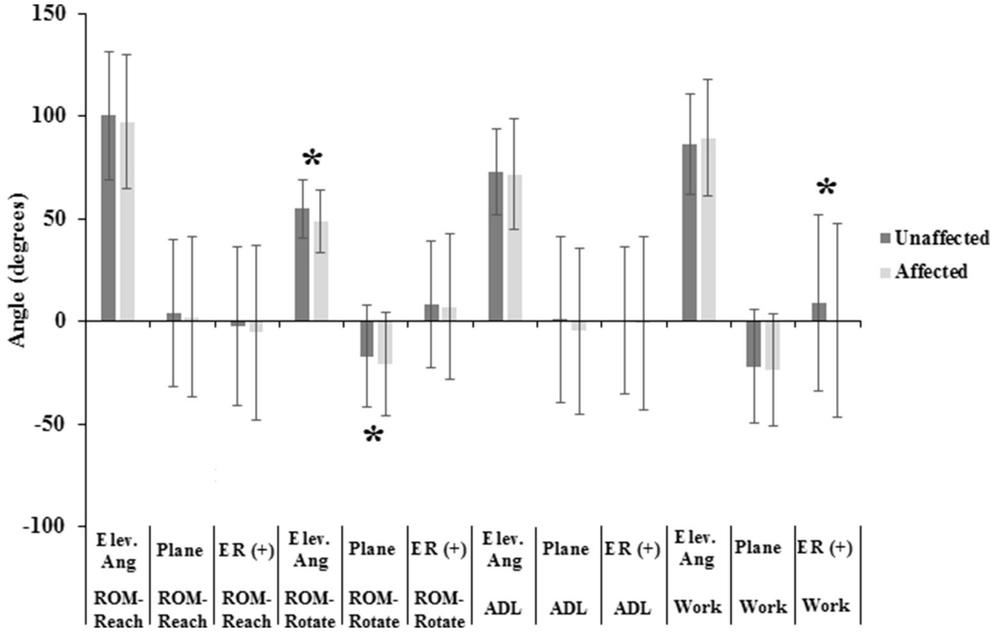

Fig. 3. Comparison of humerothoracic maximal angles between unaffected and affected sides in four types of tasks (ROM-Reach, ROM-Rotate, ADL, and Work tasks). Elevation and external rotation are shown as positive values. Plane of elevation is 0° at abduction and −90° in flexion. Statistically significant differences between sides are marked with an asterisk.

vs. −61.0°, p = 0.0073) and work tasks (−46.7° vs. −33.6°, p < 0.0001) (Fig. 3).

3.2. Scapulothoracic kinematics

Differences existed between affected and unaffected scapulothoracic ROM, maximal and minimal angle for some tasks. The affected side had increased anterior/posterior tilt ROM in ADL and work tasks (16.2° vs. 14.4°, p = 0.0428; and 16.6° vs. 14.6°, p = 0.0307, respectively). In maximal scapulothoracic angles, the affected side has more upward rotation in ROM-Rotate tasks (7.0° vs. 4.2°, p = 0.0050), and less protraction in ADL and work tasks (−28.4° vs. −31.8°, p = 0.0111; and − 26.3° vs. −30.2°, p = 0.0136, respectively) (Fig. 4). In minimal angles, the affected side had less downward rotation in ROM-Reach (−6.7° vs. −10.1°, p = 0.0003), ROM-Rotate (−1.9° vs. −5.4°, p < 0.0001), ADL (−6.3° vs. −9.2°, p = 0.0010) and work tasks (−3.5° vs. −6.7°, p < 0.0001). Additionally, the affected side had less protraction in ROM-Rotate (−37.1° vs. −40.7°, p = 0.0066) and work tasks (−44.7° vs. −49.1, p = 0.0003), and more posterior tilt in work tasks (−0.7° vs. 3.4°, p = 0.0026). Mean scapulothoracic and humerothoracic angles for unaffected and affected sides of all subjects during ROM-Reach, ROM-Rotation, ADL and work tasks are shown in Table 2.

4. Discussion

This research intended to quantify kinematic differences between affected and unaffected upper extremity motion in the BCP during range of motion, ADL and work tasks. In general, the BCP demonstrated reduced angle of elevation and increased internal rotation on the affected side, as well as reduced protraction, less downward rotation, and

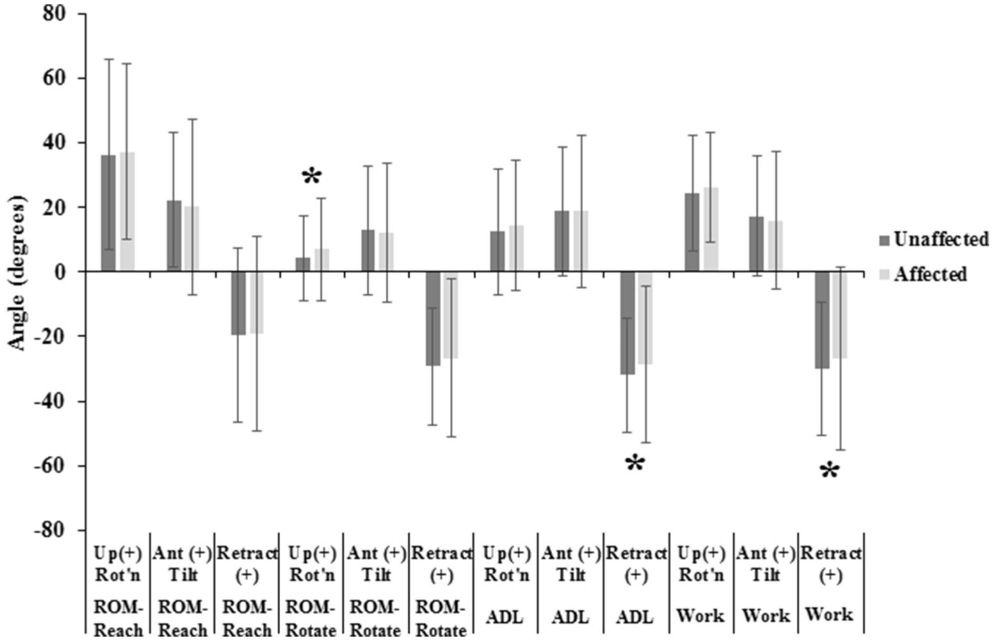

Fig. 4. Comparison of scapulothoracic maximal angles between unaffected and affected sides in four types of tasks (ROM-Reach, ROM-Rotate, ADL, and Work tasks). Upward rotation, anterior tilt, and retraction are shown as positive values. Statistically significant differences between sides are marked with an asterisk.

Table 2
Mean humerothoracic and scapulothoracic angles for ROM angles (maximum–minimum), maximum angles, and minimum angles during ROM-Reach, ROM-Rotate, ADL and Work tasks in unaffected and affected (shaded) sides. All angles are in degrees. Significant differences between affected and unaffected sides are marked with an asterisk.

Humerothoracic angles									
Task	Elevation angle (+)			Plane of elevation: −90 = flexion, 0 = abduction			External (+)/internal (−) rotation		
	ROM	Max	Min	ROM	Max	Min	ROM	Max	Min
ROM-Reach	64.9 (30.6)	100.1 (31.1)	35.2* (15.1)	39.1* (26.7)	3.9 (35.8)	−35.2 (38.6)	38.1 (31.3)	−2.1 (38.7)	−40.2 (29.8)
	67.2 (32.3)	97.0 (32.7)	29.8* (16.3)	32.2* (23.4)	2.2 (39.0)	−30.1 (38.1)	37.0 (33.0)	−5.3 (42.5)	−42.3 (29.0)
ROM-Rotate	12.2* (12.7)	54.7* (14.4)	42.5* (12.2)	19.0* (20.5)	−17.0* (24.7)	−36.2 (24.7)	26.9* (25.8)	8.1 (30.8)	−18.8* (34.3)
	9.6* (9.5)	48.7* (15.2)	39.1* (14.2)	15.3* (19.2)	−20.9* (25.1)	−36.2 (24.7)	33.6* (31.8)	7.0 (35.6)	−26.6* (41.6)
ADL	34.1 (21.8)	73.0 (21.0)	38.9* (14.2)	38.8 (30.3)	0.9 (40.6)	−38.0 (45.3)	61.4 (50.6)	0.4 (35.7)	−61.0* (41.8)
	36.1 (27.9)	71.6 (27.1)	35.4* (16.1)	34.3 (29.0)	−4.8 (40.4)	−39.1 (41.3)	68.3 (55.3)	−1.2 (42.1)	−69.5* (38.0)
Work	51.9* (22.4)	86.2 (24.2)	34.3 (16.0)	35.6 (24.5)	−22.1 (27.7)	−57.6 (27.2)	43.0 (37.3)	8.8* (43.0)	−34.2* (33.8)
	56.2* (26.0)	89.4 (28.5)	33.1 (18.2)	32.8 (26.8)	−23.8 (27.2)	−56.7 (24.0)	47.3 (46.0)	0.4* (47.1)	−46.9* (33.4)
Scapulothoracic angles									
Task	Upward (+)/downward (−) rotation			Anterior(+)/posterior (−) tilt			Retraction (+)/protraction (−)		
	ROM	Max	Min	ROM	Max	Min	ROM	Max	Min
ROM-Reach	45.6 (25.7)	36.4 (29.5)	−9.2* (13.7)	26.0 (26.2)	22.3 (20.9)	−3.7 (24.5)	24.2 (23.4)	−19.5 (27.0)	−43.7 (19.3)
	44.1 (24.0)	37.3 (27.2)	−6.8* (12.9)	23.1 (24.3)	20.2 (27.3)	−2.9 (27.2)	20.6 (22.6)	−19.1 (30.3)	−39.7 (25.5)
ROM-Rotate	9.4 (7.3)	4.4* (13.2)	−5.0* (11.7)	6.9 (6.3)	12.9 (19.9)	6.0 (19.6)	11.2 (10.7)	−29.3 (18.3)	−40.5* (16.6)
	9.0 (7.3)	7.0* (15.9)	−2.0* (14.3)	7.4 (13.2)	12.1 (21.6)	4.6 (22.9)	10.4 (10.5)	−26.8 (24.5)	−37.1* (21.2)
ADL	21.2 (13.0)	12.5 (19.5)	−8.7* (13.6)	14.5* (9.9)	18.8 (19.9)	4.3 (19.5)	14.5 (11.6)	−32.0* (17.6)	−46.4 (18.5)
	20.6 (13.1)	14.4 (20.2)	−6.3* (15.7)	16.1* (15.1)	18.9 (23.6)	2.8 (22.5)	15.8 (16.8)	−28.7* (24.2)	−44.5 (21.3)
Work	30.4 (13.0)	24.5 (18.1)	−5.9* (12.8)	14.3* (11.4)	17.4 (18.8)	3.1* (17.4)	18.9 (13.9)	−29.9* (20.6)	−48.9* (16.7)
	30.0 (12.9)	26.4 (17.0)	−3.6* (14.6)	16.5* (16.8)	16.0 (21.5)	−0.5* (25.6)	18.2 (13.9)	−26.9* (28.5)	−45.1* (21.1)

increased posterior tilt on the affected side scapula.

For most tasks, there was little difference in the overall scapulothoracic and humerothoracic task ROM (the difference between maximum and minimum achieved angles) between unaffected and affected sides. The BCP demonstrated that on the affected side, there was a reduced ROM in elevation angle during ROM-Rotate tasks (−2.3°) and in plane of elevation during ROM-Reach (−6.7°) and ROM-Rotate tasks (−3.3°). The affected side moved fewer total degrees (maximum minus minimum angle achieved) compared to the non-affected side in these tasks which could suggest that the affected side moved on a more direct path with less variability and fewer pathways available to move in due to loss of available range, pain, or constrictions (ex. cording or scar tissue build up from surgery). Similar decreases in range of motion have been observed in individuals with subacromial impingement, with symptomatic populations using a narrower ROM in flexion/extension and internal/external rotation compared to asymptomatic populations (Hall et al., 2011). Past clinical assessments have reported reductions in elevation angle ROM on the affected side during abduction (−6.4°, −7.5° and −21°) and flexion (−4.3°, −5.7°, −12°), as well as reduced external rotation ROM (−6.2°) (Hack et al., 1999; Kuehn et al., 2000; Rietman et al., 2004). Caution must be used in interpretation of total ROM as maximum and minimum absolute angle values must be considered. Total ROM is sometimes explained by a lower minimum starting angle (e.g. the affected side reached lower maximum elevation angles, but started at lower humeral elevation angles, resulting in a greater overall ROM). It is difficult to compare ROM values between previous studies as it is unknown if the starting position was consistent within tasks and studies, and if that starting position was similar to the current study.

Interpretation of both minimum and maximum humerothoracic angles revealed that the affected side reached lower elevation angles, maintained a more anterior plane of elevation and was more internally rotated. The affected humerus reached 6.5° lower maximal angles of elevation and was maintained in a more anterior plane of elevation (−21.1° vs. −17.2°) during ROM-Rotate tasks compared to the unaffected limb (Fig. 3). Three-dimensional humerothoracic kinematics of the BCP have not been described previously, but clinical assessments using goniometry have reported similar reductions in elevation angles (Hack et al., 1999; Rietman et al., 2004). The maximal angles of elevation were also lower on the unaffected side than healthy populations performing similar exertions, suggesting bilateral kinematic changes occur in the BCP. Bilateral changes have been reported by Shamley et al. (2012), who identified scapular kinematic and muscle activation changes in both arms of unilateral BCP. Compensatory changes by the unaffected side (due to overuse, radiated pain and overflow effects of radiation or surgery), as well as prophylactic bilateral mastectomy (N = 16 participants in the current study) may have altered the 'unaffected' side and resulted in bilateral changes. With the exception of the work tasks, the affected side humerus reached 3.9°–5.7° lower minimum angles of elevation. Extracted angles tend to overestimate elevation angles at lower (more neutral) arm postures, due to surrounding soft tissue of the arm and thorax which disallows alignment of the two local y-axes (Grewal et al., 2017). Further, the definition of "zero" between clinical assessments with the current work may limit direct comparison of data. Often, neutral or zero positions are defined as the anatomical stance in clinical settings, whereas zero was defined as the alignment of the humerus and thorax local coordinate systems in the current study. During work tasks, the affected humerus was 8.9° less externally rotated, similar to past research which reported BCP reductions of external rotation of $-6.2°$ (Rietman et al., 2004). Increased internal rotation for work tasks has been observed during functional tasks in individuals with rotator cuff tears (Vidt et al., 2016). This increased internal rotation may be due to deltoid and pectoral compensation for damaged rotator cuff muscles in an effort to maintain glenohumeral stability (Hawkes et al., 2012).

Adaptive changes between sides was evident through scapulothoracic changes, where the affected side was less protracted, more upwardly rotated, and more posteriorly tilted. These kinematic findings partly contrast with previous reports, although it is difficult to make direct comparisons between scapulothoracic changes reported in the BCP due to the limited number of studies available and the differing methodologies used (population characteristics, type and timing of treatment and measurements, recording methods and exertions examined). A recent study investigated scapulothoracic kinematics of the BCP during bilateral flexion, abduction and scaption, and reported that women with dominant-side mastectomies exhibited greater upward rotation during arm elevation during scaption (5.0°–9.3° more) and abduction (5.5°–11.9° more) on the affected side compared to a healthy control group (Crosbie et al., 2010). Compared to healthy controls, previous research has observed increased BCP scapular upward rotation and non-significant increases in posterior tilt (Shamley et al., 2012). Despite a lack of data available for comparison (especially for the range of tasks investigated in the current study), there was general agreement between the current study and previous work that the affected side of the BCP demonstrated more scapular posterior tilt and upward rotation (Crosbie et al., 2010; Shamley et al., 2009, 2012). Compared to previous findings, the BCP in this study had decreased protraction on the affected side. In a previous study of 11 participants performing arm elevation in the scapular plane, the affected side increased scapular protraction by 3.9°; leading to a 'winged scapula' as determined by visual clinical assessment (Lauridsen et al., 2000). Adaptive changes may reflect the scapulothoracic kinematic changes seen between sides. It has been speculated that the altered motor patterns of the scapula may be evidence of an adaptation made due to reduced frequency and amplitude of arm elevation following surgery (Crosbie et al., 2010). Increased upward rotation could also reflect a compensatory change due to postures of increased scapular protraction. Healthy populations in slouched trunk postures had more upward rotation and less posterior tilting of the scapula compared to erect posture (Kebaetse et al., 1999). Increases in posterior tilt in the current study may reflect a compensatory movement to reduce impingement risk (Ludewig and Reynolds, 2009). These adaptive scapular kinematic changes suggest probable compensation to guard against movements that are difficult, cause pain, or infer risk of subacromial impingement.

Despite modest kinematic changes between sides in the current study, these differences are important. They arguably demonstrate biological and clinical relevance, as well as mathematical (statistical) significance. The clinical importance of modest angular kinematic differences is established, as changes of just 4–6° can distinguish healthy and impinged populations (Ludewig and Cook, 2000). The considerable variability seen in the current work is expected due to the wide variety of tasks performed and differing participant factors, including cancer severity, treatments, and timing. Nonetheless, consistent differences in kinematics were found despite considerable variability, emphasizing their importance. The grouping of tasks into 3 groups was important to identify differences between task requirements (involving measures of full ROM capacity, activities of daily living and reaching work tasks) and allowed for comparisons to similar works (Hall et al., 2011; Magermans et al., 2005; Murray and Jonson, 2004). Although grouping of tasks may have reduced recognition of some differences between individual tasks, it made the interpretation of findings more generalizable so that more specific future work can be planned from this foundational type study. The fact that differences were still found despite this grouping emphasizes their importance. Small magnitude differences found between sides of the BCP emphasize the need for quantification of 3-D scapulothoracic and humerothoracic kinematics, as these changes may be difficult to evaluate using clinical assessment tools.

Due to the heterogeneity of the population examined in this work, caution must be used in interpretation and generalization of findings. Potential treatment effects, including possible bilateral changes, complicate interpretation of findings. This research did not control for hand dominance, nor side affected by cancer, which may have affected kinematics. Due to the sample size and wide variation of treatments received, it was not possible to group our participants into treatment groups, nor was it the proposed purpose of this work. By targeting subpopulations, future works could examine specific treatment effects. Obtaining detailed surgical records is recommended for future works to link the invasiveness of surgery and muscle damage with the impact on function. The results of this study provide a broad sense of capability and dysfunction of survivors in general, and are not specific to treatments received.

This investigation has produced an extensive collection of 3D humerothoracic and scapulothoracic kinematics for the BCP for many different activities. Physical function and movement strategies during a wide variety of exertions not yet examined in the literature have been provided, and the identified deficits reinforce the need for further laboratory examinations as these differences would be difficult to assess clinically. Future therapies may benefit from additional focus on postural control such as scapular retraction, and encourage movements that involve external rotation, particularly on the affected side. Accurate documentation of physical capability and dysfunction is the first step towards developing targeted treatment and preventative strategies for this disabled population and future research must continue to examine survivor capability and dysfunction to extend these preliminary observations to actionable population-specific recommendations.

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