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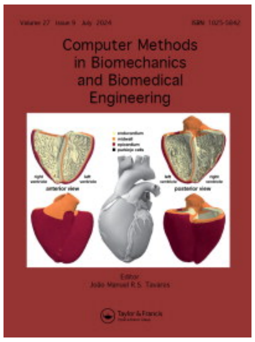

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Spinal joint moment prediction following simulated breast surgery using a female whole-body musculoskeletal model

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ABSTRACT
This study aimed to use a musculoskeletal model to predict changes in spinal moments following simulated breast surgery. A female full body musculoskeletal model with a fully articulated thoracolumbar spine and independent moveable breast segments was customised for this study. Key findings suggest that the simulated removal of breast tissue (750 g to 1501 g) can reduce the magnitude of lumbar spine extensor moments by >0.05 Nm/kg during walking and jogging. A customised female whole-body musculoskeletal model is capable of providing a first approximation of changes in spinal loading following simulated breast surgery.

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KEYWORDS
Simulation; rehabilitation; spine; mastectomy

Introduction

Treatment for breast cancer varies depending on the stage of cancer at diagnosis, age of the individual diagnosed, and the availability of different treatment services, approximately 81% of patients diagnosed with breast cancer have surgery to remove a tumour (Cancer Research UK 2023). Whether breast conserving surgery (BCS) or mastectomy performed with or without reconstruction, all types of breast surgery will alter the soft tissue mass on the patient's torso. A change in the anterior breast mass on the torso may lead to changes in the spinal joint moments required to maintain posture whilst standing or during everyday physical activity such as walking or jogging. For example, a bi-lateral removal of anterior breast mass may reduce extensor spinal moments, whereas a uni-lateral breast mass removal may also alter the frontal plane spinal moments, required to maintain posture (Oh et al. 2021). Spinal loading plays an important role in back pain (Actis et al. 2018) and previous research has reported that a change of 0.05 Nm/kg in lumbar spine moments as being the difference between participants with and without back pain (Hasegawa et al. 2018).

A human musculoskeletal model has the advantage over experimental studies as the model can conduct an 'ideal' experiment whereby one variable is changed to directly understand its impact on another, hence the effect of changes in a moving breast mass on internal loading is possible to predict. The soft tissue of the female breasts have a combined mass of 0.92 kg for a (UK average) bra size of 34D (Turner and Dujon 2005), and move 15 cm when unsupported during running (Scurr et al. 2011).

Whilst computer modelling techniques are commonly used within other surgical fields to predict surgical outcomes or consequences on the musculoskeletal system, for example, simulating tibialis anterior muscle transfer for congenital clubfoot (Li et al. 2019) or tendon transfer surgery for ulnar median nerve palsy (Montgomery et al. 2013) there have been limited applications in the breast surgical field. At present the authors are not aware of any whole-body female musculoskeletal models with dynamic breast segments, however a static ellipsoid breast segment has been included in a musculoskeletal model of a pregnant female (Haddox et al. 2020) used to investigate lumbar spine moments. Whilst there are many finite element models of the breast, most are developed to predict localised deformation during simulated mammographic compression (Said et al. 2023) or to predict breast surgical outcomes (Amini and Kersten-Oertel 2022). These models are successful at modelling the localised deformation of the breast but the models are unable to consider the wider consequence on the muscular skeletal system.

Therefore, the aim of this study was to utilise a whole-body female musculoskeletal model, with

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individual moveable breast segments, to estimate the effect of simulated breast surgery on spinal joint moments during everyday tasks such as standing, walking and jogging.

Material and methods

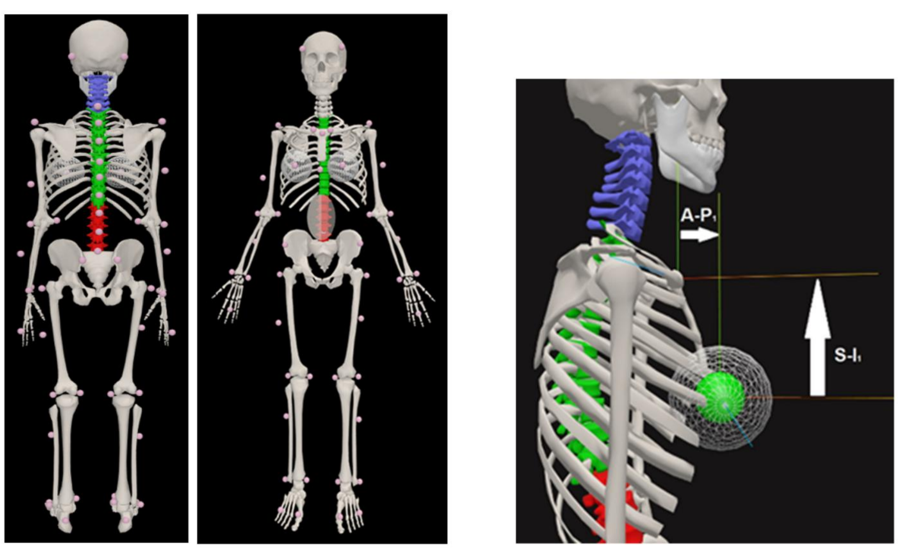
Data collection consisted of one testing laboratory session whereby there was a professional bra fit, static breast measurements and kinematic and kinetic data were captured.

Participants

Following institutional ethical approval, one healthy female (74.6 kg, 1.79 m, 26 years, UK bra size 34DD) provided written informed consent to participant in this study. The participant had not undergone any surgical procedures to their breasts and were not pregnant or currently breastfeeding. The participants had their bra size assessed by a trained bra fitter using best-fit criteria (McGhee and Steele 2010; White and Scurr 2012). One participant was recruited for this study, similar to previous modelling research (Pain and Challis 2006; Mills et al. 2008; Masters and Challis 2022), as the purpose of this paper was to understand the mechanics of how simulated breast surgery effects loading on the spine rather than variability of individuals' spinal moments.

Data collection

Stretch stature and body mass measurements were taken to a precision of 10 mm and 0.1 kg respectively, using a Seca free-standing height measure and calibrated Seca scales. Fifty-seven reflective markers were attached to key anatomical locations (Figure 1a), with a handheld ultrasound machine (Sonosite Edge, USA) used to guide marker placement on the spine. One additional marker was placed on the nipple of each breast over the bra. Three force platforms (Kistler, Switzerland; 1000 Hz) and a 19-camera motion capture system (Qualisys, Sweden; 250 Hz) were synchronised for data collection. The left and right breast boundaries were identified using the folding line method (Lee et al. 2004) and the most superior, inferior, medial and lateral position on the boundary marked using a surgical marker pen. The participant was asked to complete a standing and walking trial whilst wearing an everyday bra (EB) (Marks & Spencer) and the jogging trial whilst wearing a sports bra (SB) (Triumph, Triaction). The participant was asked to stand bare-breasted statically for 15s whilst a hand-held 3D surface scanner (Artec Eva) was used to record the torso and breast geometry for subsequent calculation of each breast volume, breast mass and centre of mass location. Following a gentle warm up the participant was asked to stand statically for 5 s and then asked to perform a walking trial at a self-selected speed (1.98 m/s) in their everyday bra and a jogging trial at a self-selected speed of 3.14 m/s in



(a) (b)

Figure 1. (a) Marker locations on participant (b) example representation of the breast attachment model. Anterior-posterior (A-P_1) generalised force between torso and breast Centre of mass (green circle); Superior-inferior (S-I_1) generalised force between torso and breast Centre of mass (green circle).

their sports bra, whilst kinematic and kinetic data were collected.

Data processing and analysis

Surface breast scans were processed in Artec Studio 17 Professional (Artec3D, Luxembourg) with a 3D resolution of 0.5 mm. Using the marked breast boundary in the no bra condition, each breast was extracted from the torso. The posterior of the breast was flat filled and volume calculated using the software. Each breast mass was calculated using the breast volume and breast density of 945 kg/m^3 (Sanchez et al. 2016), the mass of each breast was 0.747 kg (right) and 0.754 kg (left). The breast centre of mass position was calculated using the 3D surface scanned breast data and assuming each breast was a geometric solid hemisphere (Haddox et al. 2020). The centre of mass of the hemisphere lies on the vertical line passing through the centre of the hemisphere and normal to the base. The centre of mass was calculated using $Y = 3R/8$; where 'Y' was the distance to the centre of mass and 'R' was the radius of the hemisphere. The radius was calculated from the nipple marker (breast apex) to the breast boundary. The centre of mass was at a distance Y anteriorly from the breast base towards the breast apex (Figure 2). A virtual breast centre of mass marker was created in all trials within the Qualisys Track Manager software. All kinematic and kinetic data were processed and exported *via* a customised MatLab script for importing into OpenSim (Simtk.org). The standard OpenSim workflow was followed to ensure the generic female model was scaled to the participant based on marker data in the static trial. The breasts were not included in the scaling process and their mass was included within the torso segment. Following successful completion of the scaling process the mass of each breast was subtracted from the calculated torso mass (16.49 kg) and added to the relevant breast segment, as such the whole-body mass remained unchanged. The Inverse Kinematics Tool, in OpenSim, was used to find the values for the generalized coordinates (joint angles and positions) in the model that best matched the experimental kinematics using a weighted least squares problem, whose solution aimed to minimise both marker and coordinate errors. The Root Mean Square (RMS) error between the experimental breast markers and the inverse kinematics breast markers during the jogging trial were 0.004 m (left breast) and 0.003 m (right breast). Additionally, all mean and maximum errors between the experimental data and model inverse kinematics solutions were within the OpenSim recommended maximal value of 2 cm for RMS value and 2 to 4 cm for the maximum (Hicks 2018) for standing, walking and jogging. The resulting kinematics were filtered with a low pass Butterworth filter with a cut-off frequency of 5 Hz (Rácz and Kiss 2021). Subsequently, the inverse kinematics solution were combined with the ground reaction force data within the Inverse Dynamics Tool for each simulated breast surgery condition in order to calculate the spinal joint moments during the activities of standing, walking and jogging.

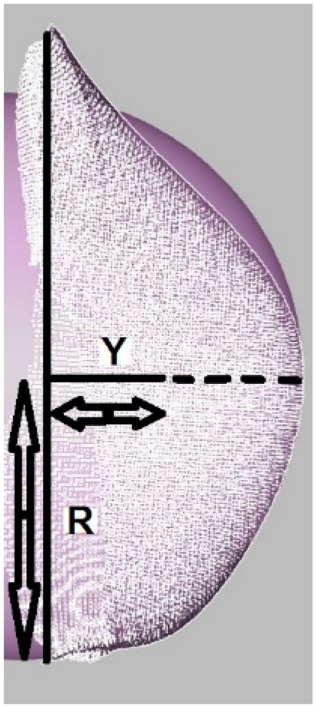


Figure 2. Geometric representation of breast Centre of mass calculation. Sagittal plane breast view from breast surface scan (dotted) and hemisphere assumption overlay (solid).

Musculoskeletal model

A validated female full body model (Bruno et al. 2017; Burkhart et al. 2020) with a fully articulated thoracolumbar spine (T1 through L5), with three rotational degrees-of-freedom at each inter-vertebral joint was selected for customisation for this study. The female whole-body model was modified to include two breast segments positioned on the anterior of the torso. Given previous literature has defined the motion of the breast in three dimensions (Scurr et al. 2011), each breast segment was represented by a point mass and attached *via* a three degree of freedom sliding joint (Figure 1b) to the torso allowing translation of the breast segment relative to torso segment in three planes (anterior/posterior, medial/lateral, superior/inferior). The sliding (breast) joint provides a single coordinate along the common X-axis of the parent (torso) and child (breast) joint frames. The Inverse Dynamics calculates the net generalized forces at all degrees of freedom and these generalized forces account for the breast motion and applied external forces when calculating new generalized forces at each breast joint. The breast joint forces are transferred between consecutive bodies as a result of all loads acting on the model.

The initial position of each breast segment was defined by the centre of mass position of the breast during standing. To simulate the breast surgical conditions the masses of the breast segments were altered, then the same segment kinematics re-run and the new joint moments calculated *via* inverse dynamics. Firstly, a simulation was run with no changes to the participant's breast mass (Nat). Next, to simulate a simple unilateral mastectomy (removal of all breast tissue), the left breast mass was reduced to zero (Uni) and finally to simulate an extreme simple bi-lateral mastectomy both the left and right breast mass were reduced to zero (Bi) and the segment kinematics for standing, walking and jogging were re-run. Whilst BCS aims to preserve the maximum amount of healthy breast tissue whilst removing the affected tissue, these simulations represent ~31% of patients that require a simple mastectomy (National Cancer Institute 2023), to understand how the removal of all breast tissue effects spinal joint moments.

The local coordinate system for the torso was defined by markers on the sternal notch, xiphoid process, 7th cervical vertebra and 8th thoracic vertebra (Wu et al. 2005) and used to calculate the flexion/extension, lateral bend and axial rotation angle of the torso body within the global coordinate system (z = vertical, y = medial/lateral, x = anterior/posterior) for the standing, walking and jogging trials. Breast centre of mass position and breast joint force (the force applied by the breasts on the torso at the sliding joint) was calculated during inverse dynamics in three directions (anterior-posterior, medial-lateral, superior-inferior) within the torso local coordinate system. For each simulated breast surgical condition, net joint moment of each lumbar (L1-L5) and thoracic (T1-T12) spinal joints were mean averaged at each time point to create a single net lumbar and thoracic moment time history. Each time history was time normalised to 101 data points (i.e. 0–100% of the gait cycle at 1% increments). Key events within the gait cycle, such as right and left foot contact were highlighted on the time histories and identified using the vertical ground reaction force (threshold >10 N) data. The minimum and maximum spinal moment in each direction was reported as peak moment for the walking and jogging gait cycle. Additionally, the net lumbar and thoracic joint moment over the gait cycle was calculated. All spinal joint moment data were normalised to the participant's mass (74.6 kg). Finally, only reporting the absolute differences between the estimated spinal moments could be misleading because the interpretation of the differences relates to the magnitude of predicted spinal moments. Therefore, the relative differences in the predicted maximum, minimum and net spinal moments with respect to the natural breast condition (Nat) were calculated for each simulated breast surgery (Akhavanfar et al. 2022) (equation 1 – example for maximum lumbar moments).

$$\text{Relative Difference}_{\text{condition i}} = \frac{\max \left[Lumbar\ conditon\ \text{i}) - \max(Lumbar\ condition'natural' \right]}{\max\ Lumbar\ condition'natural'} \text{x } 100 \qquad (1)$$

Results

Standing

During standing the torso remained in slight extension (3.1°), right bend (-1.3°) and clockwise rotation (1.8°) within the global coordinate system. Both breasts were positioned 0.09 m anterior and −0.18 m inferior, the left and right breast were 0.12 m and −0.11 m lateral respectively, of the torso origin in the torso local coordinate system. Within the 'Natural' condition the breasts produce a force on the torso of 0.2 N anteriorly, 0.4 N medially and 7.4 N inferiorly. The greatest change in lumbar joint moments occurred in flexion/extension, decreasing by 0.023 Nm/kg and 0.031 Nm/kg within the thoracic region, between Natural and Bi-lateral mastectomy conditions. There were minimal changes (<0.02 Nm/kg) in other directions at either the lumbar or thoracic regions of the spine (Table 1).

Table 1. Net lumbar and thoracic joint moments during standing (Nm/kg), including relative percentage difference in brackets, between simulated surgical conditions.

Spine region	Direction	Nat	Uni	Bi
		Surgical condition		
Lumbar	Flexion/Extension	0.022	0.010 (-55%)	−0.001 (-105%)
	Lateral Bend	0.027	0.015 (-44%)	0.025 (-7%)
	Axial Rotation	0.016	0.020 (25%)	0.018 (13%)
Thoracic	Flexion/Extension	0.101	0.085 (-16%)	0.070 (-31%)
	Lateral Bend	−0.002	−0.012 (500%)	−0.001 (-50%)
	Axial Rotation	0.012	0.010 (-17%)	0.011 (-8%)

Flexion(-) Extension(+); Left Bend(-) Right Bend(+); Clockwise rotation(-) Anticlockwise rotation(+).
Nat = Natural Breasts; Uni = Simulated unilateral mastectomy; Bi = Simulated bilateral mastectomy.

Walking

During walking the torso remained in slight extension, ranging from −16° to −9°, left and right bending ranged from −6° to 5° and axial rotation ranged from 2° to 12° during the walking gait cycle. Within the 'natural' condition both breasts positions changed by ~0.01 m in all directions within the local coordinate system of the torso, across the gait cycle. The force induced on the torso by the moving breast mass during walking ranged from 1.1 N to −5.5 N in the anterior-posterior, 2.1 N to − 2.3 N in the medial-lateral and 12.0 N to 2.5 N in the superior-inferior directions (Figure 3).

Simulated breast surgery predicts changes of up to 0.04 Nm/kg in net lumbar or thoracic spinal moments during a walking gait cycle (Table 2), with the greatest difference between the natural and bi-lateral

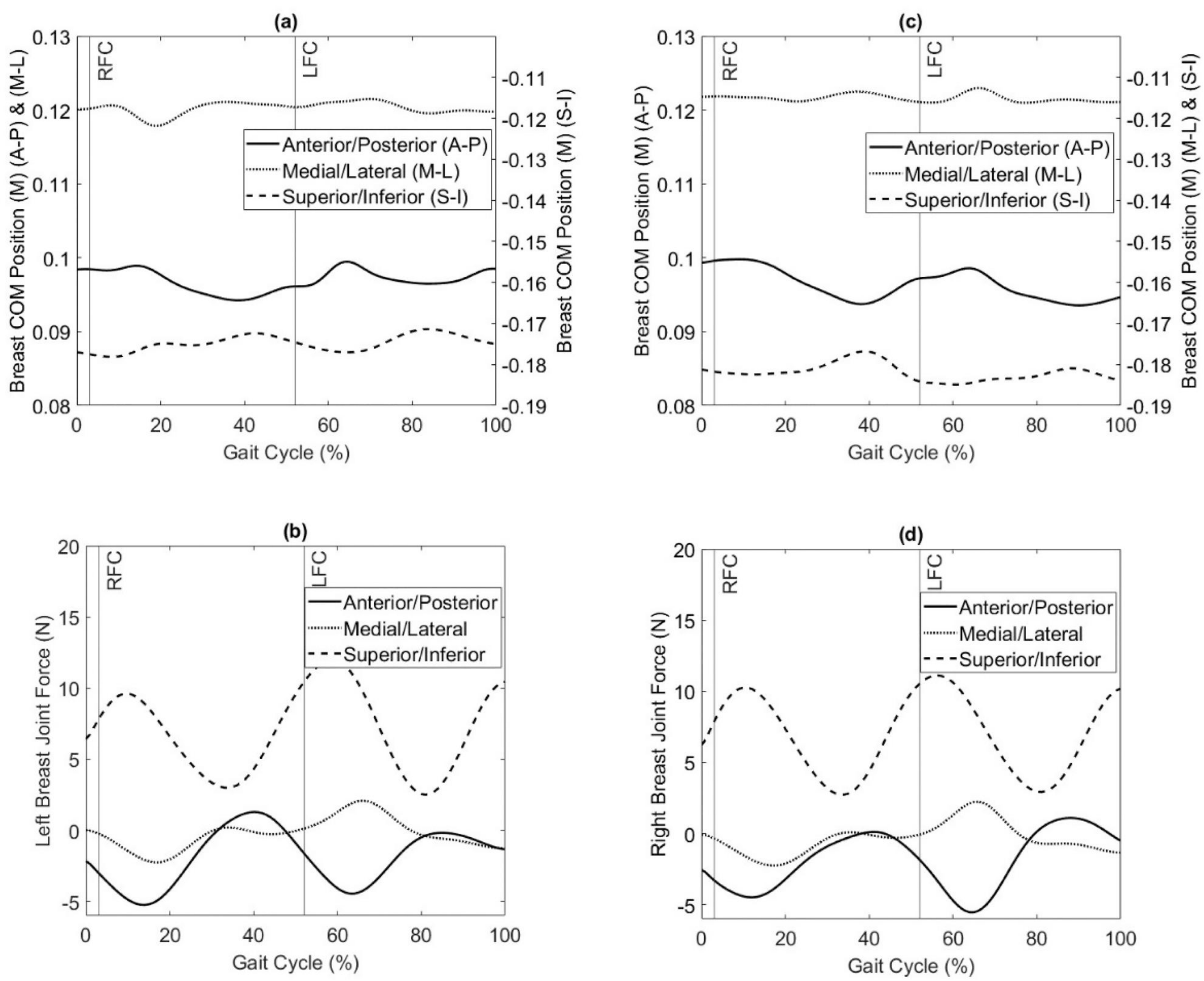


Figure 3. Breast motion and joint force during the walking gait cycle (natural breast condition). (a) left breast position, (b) left breast joint force, (c) right breast position, (d) right breast joint force). RFC = right foot contact; LFC = left foot contact.

Table 2. Peak and net lumbar and thoracic joint moments during one walking gait cycle (Nm/kg), including relative percentage difference, between simulated surgical conditions.

Spine region	Peak or net	Direction	Surgical condition Nat	Uni	Bi
Lumbar	Peak	Flexion	−0.046	−0.049 (7%)	−0.056 (22%)
		Extension	0.564	0.534 (-5%)	0.505 (-10%)
		Left Bend	−0.254	−0.265 (4%)	−0.244 (-4%)
		Right Bend	0.432	0.400 (-7%)	0.407 (-6%)
		Clockwise	−0.242	−0.239 (-1%)	−0.234 (-3%)
		Anticlockwise	0.214	0.206 (-4%)	0.201 (-6%)
	Net	Flexion/Extension	0.229	0.212 (-7%)	0.195 (-15%)
		Lateral Bend	0.011	−0.009 (-182%)	0.001 (-91%)
		Axial Rotation	−0.002	−0.007 (250%)	−0.007 (250%)
Thoracic	Peak	Flexion	No Flex	No Flex	No Flex
		Extension	0.242	0.220 (-9%)	0.200 (-17%)
		Left Bend	−0.183	−0.190 (4%)	−0.176 (-4%)
		Right Bend	0.271	0.250 (-8%)	0.258 (-5%)
		Clockwise	−0.126	−0.130 (3%)	−0.123 (-2%)
		Anticlockwise	0.119	0.084 (-29%)	0.083 (-30%)
	Net	Flexion/Extension	0.130	0.113 (-13%)	0.099 (-24%)
		Lateral Bend	−0.001	−0.011 (1000%)	−0.003 (200%)
		Axial Rotation	−0.006	−0.017 (183%)	−0.012 (100%)

Flexion(-) Extension(+); Left Bend(-) Right Bend(+); Clockwise rotation(-) Anticlockwise rotation(+).
Nat = Natural Breasts; Uni = Simulated unilateral mastectomy; Bi = Simulated bilateral mastectomy.

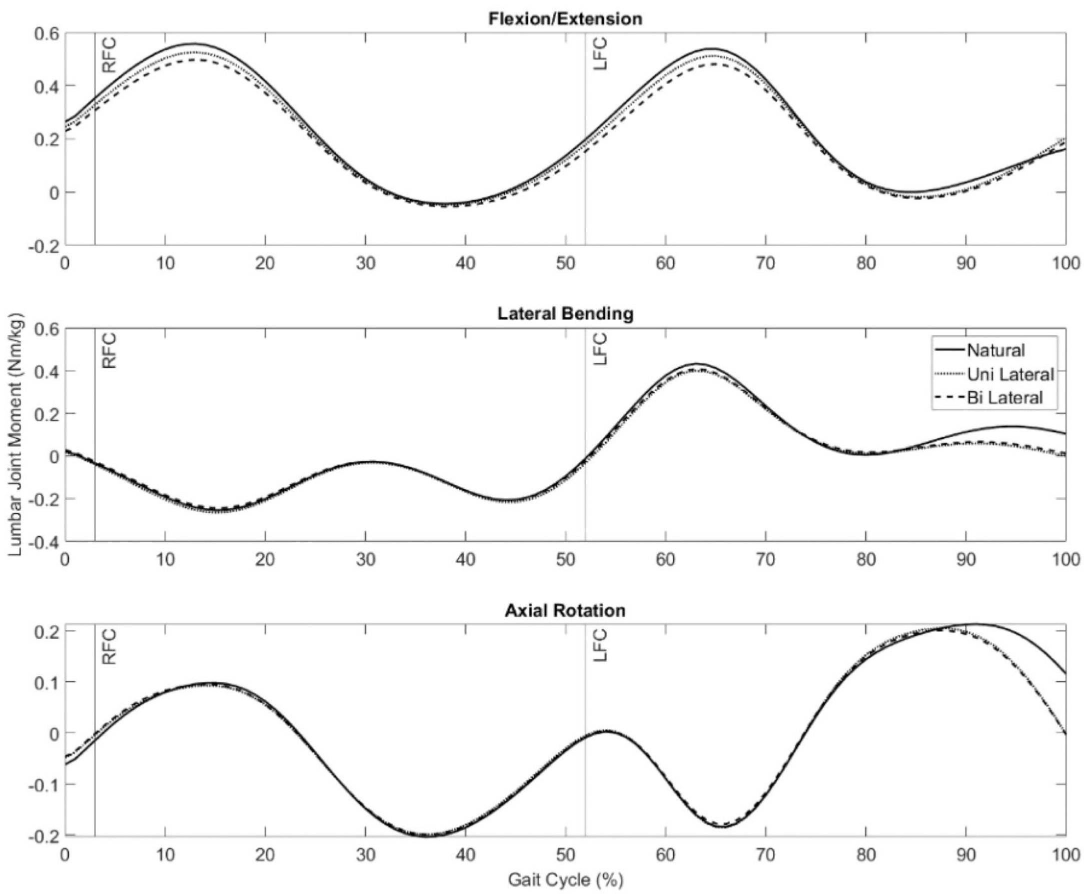


Figure 4. Lumbar spine moments during the walking gait cycle in the natural condition (no change in breast mass), the uni-lateral condition (removal of left breast mass), the Bi-lateral condition (removal of both breast masses) (RFC = right foot contact; LFC = left foot contact).

mastectomy simulated conditions. The greatest change in peak joint moments occurred within the extensors of the lumbar spine (0.05 Nm/kg), indicating a reduced extension moment within this region when a bi-lateral breast surgery is simulated. Although the greatest change in peak moment occurred within the lumbar region of the spine, the thoracic region exhibited temporal and magnitude differences between simulated surgical conditions (Figures 4 and 5). Whilst a simulated uni-lateral mastectomy had

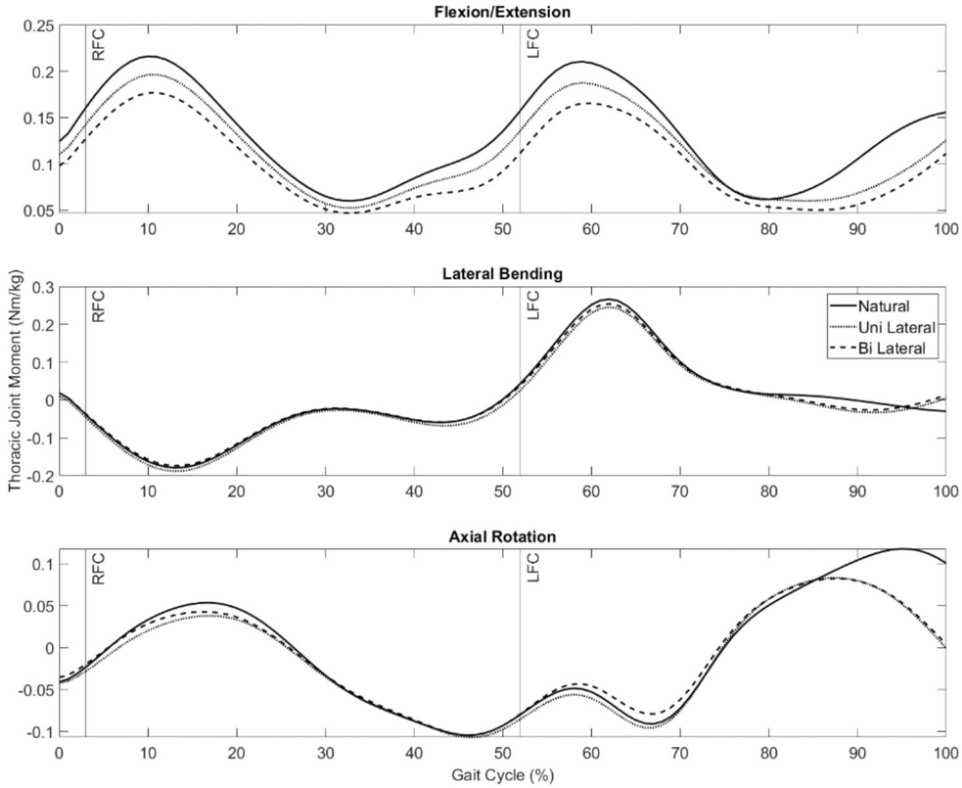


Figure 5. Thoracic spine moments during the walking gait cycle in the natural condition (no change in breast mass), the uni-lateral condition (removal of left breast mass), the Bi-lateral condition (removal of both breast masses) (RFC = right foot contact; LFC = left foot contact).

minimal differences between the natural breast condition, the bi-lateral mastectomy exhibited notable changes. Peaks in joint moments tended to occur earlier in the gait cycle (following foot contact) for the bi-lateral mastectomy condition compared to the natural or uni-lateral mastectomy conditions (Figure 4) and these peaks were up to 0.03 Nm/kg different.

Jogging

During jogging the torso ranged from −15° extension to 24° flexion, −10° left to 8° right bending and from −24° to −14° and axial rotation within the jogging gait cycle. Within the 'Natural' condition both breasts positions changed by <0.01 m in the anterior-posterior and medial-lateral directions and 0.02 m in the superior-inferior direction within the local coordinate system of the torso, across the jogging gait cycle. The force induced on the torso by the moving breast mass during jogging ranged from 1.5 N to −8.5 N in the anterior-posterior, 3.8 N to −5.1 N in the medial-lateral and −5.4 N to 23.5 N in the superior-inferior directions (Figure 6).

Simulated breast surgery predicts changes of up to 0.07 Nm/kg (17%) in net lumbar or thoracic spinal moments during a jogging gait cycle (Table 3), with the greatest difference between the natural and bi-lateral mastectomy simulated conditions. The greatest change in peak joint moments occurred within the extensors of the lumbar spine (0.12 Nm/kg; −9%), indicating a reduced extension moment within this region when a bi-lateral breast surgery is simulated. Although the greatest change in peak moment occurred within the lumbar region of the spine, the thoracic region exhibited magnitude differences between simulated surgical conditions (Figure 7 and 8) in flexion/extension. The simulated uni-lateral and bi-lateral mastectomy had minimal differences (<0.05 Nm/kg) between the natural breast condition, except for lumbar flexion (>0.05 Nm/kg).

Discussion

This study aimed to utilise a whole-body female musculoskeletal model, with individual moveable breast segments, to estimate the effect of simulated breast surgery on spinal joint moments during everyday tasks such as standing, walking and jogging. Key findings suggest that the simulated removal of breast tissue can reduce the magnitude of lumbar spine

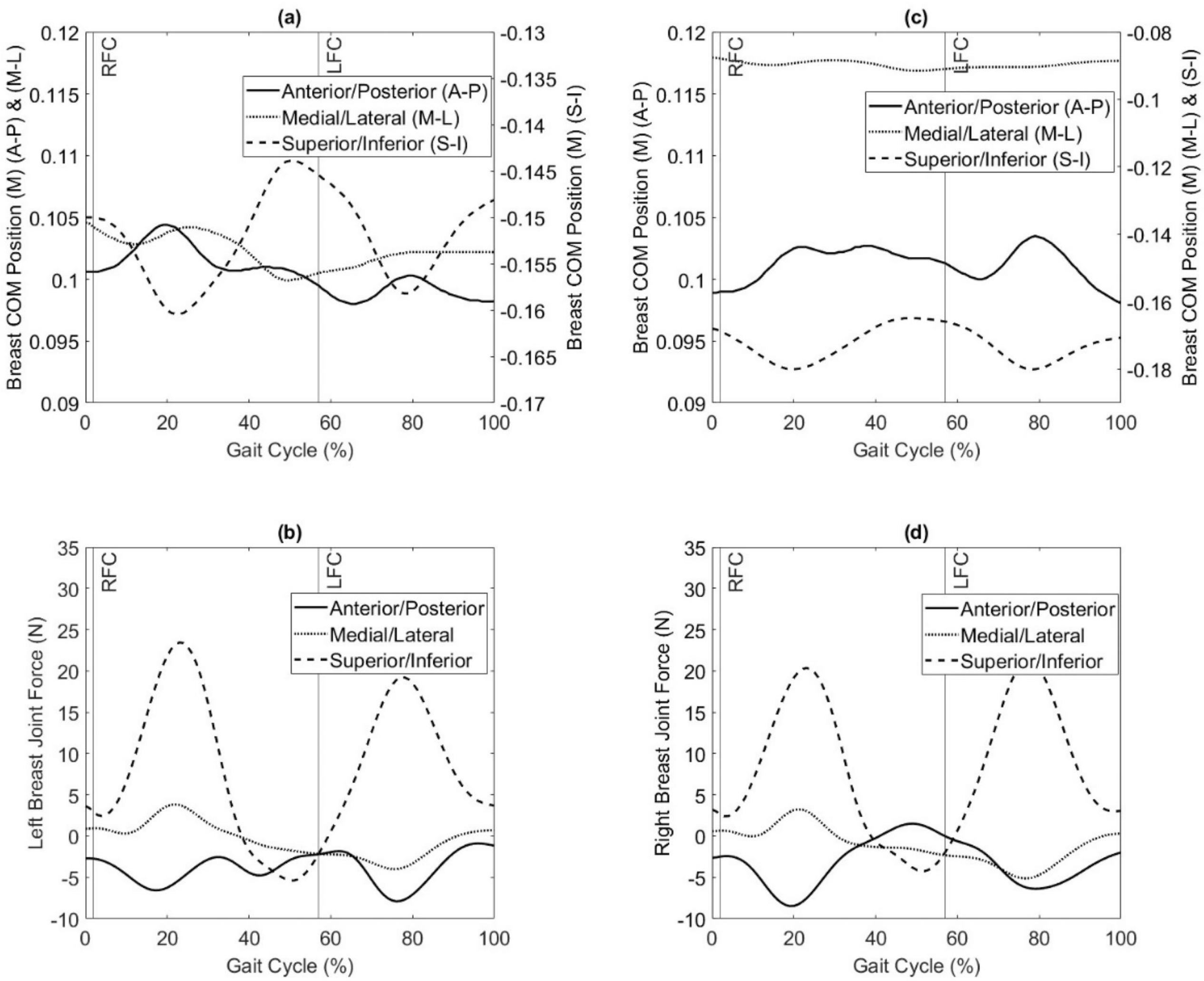


Figure 6. Breast motion and joint force during the jogging gait cycle (natural breast condition). (a) left breast position, (b) left breast joint force, (c) right breast position, (d) right breast joint force). RFC = right foot contact; LFC = left foot contact.

Table 3. Peak and net lumbar and thoracic joint moments during one jogging gait cycle (Nm/kg), including relative percentage difference, between simulated surgical conditions.

Spine region	Peak or net	Direction	Surgical condition Nat Uni Bi		
Lumbar	Peak	Flexion	−0.066	−0.067 (2%)	−0.073 (11%)
		Extension	1.316	1.253 (-5%)	1.198 (-9%)
		Left Bend	−0.591	−0.611 (3%)	−0.576 (-3%)
		Right Bend	0.596	0.557 (-7%)	0.578 (-3%)
		Clockwise	−0.713	−0.713 (0%)	−0.709 (-1%)
		Anticlockwise	0.710	0.708 (0%)	0.708 (0%)
	Net	Flexion/Extension	0.430	0.378 (-12%)	0.357 (-17%)
		Lateral Bend	0.055	0.044 (-20%)	0.056 (2%)
		Axial Rotation	0.081	0.078 (-4%)	0.079 (-2%)
Thoracic	Peak	Flexion	−0.081	−0.077 (-5%)	−0.075 (-7%)
		Extension	0.442	0.404 (-9%)	0.371 (-16%)
		Left Bend	−0.408	−0.423 (4%)	−0.397 (-3%)
		Right Bend	0.423	0.393 (-7%)	0.407 (-4%)
		Clockwise	−0.420	−0.427 (2%)	−0.423 (1%)
		Anticlockwise	0.393	0.388 (-1%)	0.382 (-3%)
	Net	Flexion/Extension	0.132	0.117 (-11%)	0.102 (-23%)
		Lateral Bend	0.012	0.002 (-83%)	0.010 (-17%)
		Axial Rotation	0.060	0.053 (-12%)	0.056 (-7%)

Flexion(-) Extension(+); Left Bend(-) Right Bend(+); Clockwise rotation(-) Anticlockwise rotation(+).
Nat = Natural Breasts; Uni = Simulated unilateral mastectomy; Bi = Simulated bilateral mastectomy.

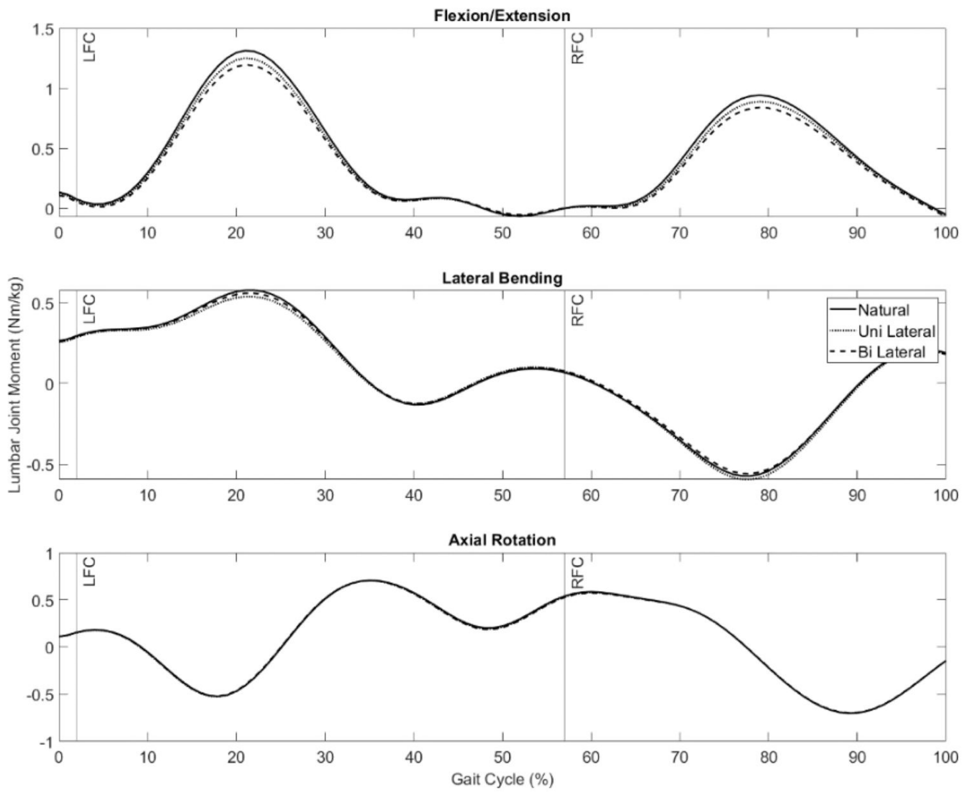


Figure 7. Lumbar spine moments during the jogging gait cycle in the natural condition (no change in breast mass), the uni-lateral condition (removal of left breast mass), the Bi-lateral condition (removal of both breast masses) (RFC = right foot contact; LFC = left foot contact).

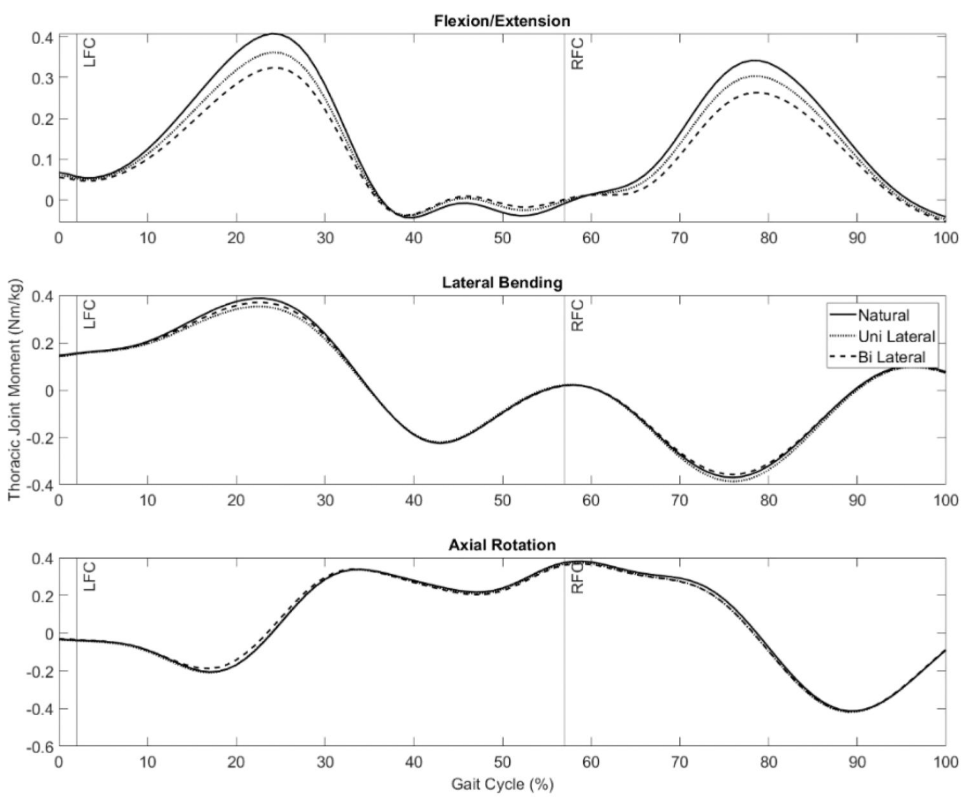


Figure 8. Thoracic spine moments during the jogging gait cycle in the natural condition (no change in breast mass), the uni-lateral condition (removal of left breast mass), the Bi-lateral condition (removal of both breast masses) (RFC = right foot contact; LFC = left foot contact).

extensor moments by up to 0.03 Nm/kg (31%) when standing, 0.05 Nm/kg (10%) during walking and 0.12 Nm/kg (9%) during jogging. These results confirm that a female whole-body musculoskeletal model scaled to represent a specific subject can be used to provide a first approximation of changes in spinal loading following simulated breast surgery, personalised to a patient.

Whether standing, walking or jogging a similar consequence upon the spinal moments occurs following the simulated surgical procedures in this study, however the magnitude of the differences varies between activities. Previous research has suggested that a change in 0.05 Nm/kg in spinal joint moments is sufficient to distinguish between back pain and non-back pain suffers (Hasegawa et al. 2018). Therefore, it is important to be mindful of this threshold when interpreting the findings of this study. Simulated lumbar flexor moments increased (<0.05 Nm/kg) and extensors moments decreased (>0.05 Nm/kg) following both uni-lateral and bi-lateral simulated breast surgery, highlighting that any reduction in breast mass may potentially reduce the muscular effort in the back extensors required to maintain the same kinematics, for the participant model in this study. Therefore, a simulated bi-lateral mastectomy (~1.5 kg tissue removal) reduced the lumbar extensor moments by >0.05 Nm/kg, which has potential to reduce the occurrence of back pain.

The simulated uni-lateral removal of the left breast (0.754 kg) resulted in an increased (up to 0.02 Nm/kg during jogging) left bending moment in the lumbar and thoracic regions of the spine when compared to the natural condition. Although the magnitude was lower than the threshold (0.05 Nm/kg) used to distinguish between back pain and non-back pain sufferers (Hasegawa et al. 2018), additional changes in lateral moments may have further implication on back pain. Furthermore, imbalances in lumbar spine loading have been associated with lower back pain patients (Oddsson and De Luca 2003) and the results of this study show a 0.054 Nm/kg difference between left and right bending moments during jogging. Therefore, breast reconstruction, implant or prothesis may help to reduce any asymmetry in breast mass and its consequence on the musculoskeletal system. It is also recommended that breast surgeons continue to aim to conserve the maximum amount of healthy breast tissue and remove only the affected tissue to minimise asymmetry of breast mass and subsequent effects on spinal loading.

It is noted that this study asked the participant to stand for 15 s and perform a short walk and jog whereby one gait cycle of each were analysed for the surgical simulations. Given occupational and everyday tasks often involve standing for long periods of time and adherence to national exercise guidance will mean repeated gait cycles, the cumulative effects of these changes in spinal moments may require further consideration and have implications on wider injury risk. The computer simulation model, scaled to the participant in this study, incorporates sufficient complexity (such as a fully articulated thoracolumbar spine and independent moveable breasts) in order to predict the effect of surgical outcomes on the spine. Future work could develop this model to include the musculature and investigate directly any changes in muscular demand following simulated breast surgery. Potential future patients could then benefit from personalised pre-surgery strengthening exercises to minimise post-surgical consequences, improving patient outcomes in terms of return to work and an active lifestyle.

This study assumes a simple uni or bi-lateral mastectomy whereby all breast is removed, and the results have shown consequences on the spine that exceed the differences in spinal moments (0.05 Nm/kg) between back pain and non-back pain sufferers as well as estimating asymmetrical loading. Future work could investigate the effects of incremental changes in breast mass removal (breast conserving surgery) to determine a mass removal threshold that minimises a 'meaningful' asymmetrical spinal loading. Although the results of this study demonstrate differences in spinal loading between simulated surgical scenarios, the limitations associated with this modelling approach are important to discuss. The actual data presented may vary given the single subject nature of the model, thus aspects such as the individual gait kinematics of the participant may influence the exact spinal moments reported. However, it is also important to acknowledge that the same input kinematics were used throughout and the influence of simulated surgery investigated. The hemispherical assumption used to calculate the centre of mass of the breast is similar to previous literature, however this assumption may not be appropriate for participants with breast ptosis, as it assumes the breast volume is equally distributed either side of the breast apex and that the breast apex is at the same location as the nipple. The movement of the breast tissue, measured using the markers and motion capture system, provided kinematic outcomes that included the viscoelastic effects of the breast tissue and could then be used to investigate the inverse dynamics outcomes based on the dynamic breast motion. However, the inverse dynamics approach depends upon the quality of the kinematics data used to drive the model and a future forward dynamics model would enable manipulation of viscoelastic soft tissue properties to determine how they affect soft tissue motion.

In conclusion, whilst caution must be applied when interpreting the magnitude of differences in spinal loading between the simulated surgical scenarios, there is evidence to suggest that a customised female whole-body musculoskeletal model was capable of providing a first approximation of changes in spinal loading following simulated breast surgery. Simulated breast surgery conditions have shown that spinal joint moment changes can exceed the threshold (0.05 Nm/kg) for distinguishing between back pain in a participant representative of typical females who undergo such surgery. This insight can inform the future model development and potentially personalised pre and post-operative rehabilitation recommendations to minimise the impact of breast surgery on spinal loading for unilateral and bilateral breast surgery patients.

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