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ORIGINAL ARTICLE

Motion at the Sternal Edges During Upper Limb and Trunk Tasks In-Vivo as Measured by Real-Time Ultrasound Following Cardiac Surgery: A Three-Month Prospective, Observational Study

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Background Despite a paucity of evidence, patients following cardiac surgery via median sternotomy are routinely prescribed sternal precautions that restrict upper limb and trunk movements, with the rationale of reducing postoperative sternal complications such as sternal wound dehiscence, instability, infection and/or pain. The primary aim of this study was to measure motion at the sternal edges during dynamic upper limb and trunk tasks to better inform future sternal precautions and optimise postoperative recovery. Motion at the sternal edges was measured using ultrasound, which has been demonstrated to be a clinically valid and reliable measure in patients following cardiac surgery.

Methods Seventy-five (75) patients following cardiac surgery via median sternotomy with conventional stainless steel wire closure were recruited. Motion at the sternal edges in the lateral (coronal plane) and anterior-posterior (sagittal plane) directions was measured at the level of the fourth intercostal space (mid-sternum) using ultrasound. Ultrasound measures were taken at rest and during five dynamic upper limb and trunk tasks (deep inspiration, cough, unilateral and bilateral upper limb elevation and sit to stand), over the first 3 postoperative months (3 to 7 days, 6 weeks and 3 months postoperatively). Sternal pain, functional status and sternal healing were also observed over the same postoperative period.

Results The magnitude of overlap of the sternal edges in the lateral direction, and separation of the sternal edges in the anterior-posterior direction, both significantly decreased by 0.01 cm, over the first 3 postoperative months ($p < 0.01$). Coughing, however, produced a significant increase in separation of the sternal edges in the lateral direction (0.01–0.02 cm) and pain (12–63%), compared to rest and all other tasks, at each postoperative time point ($p < 0.01$). Additionally, there was a significant decrease in sternal pain (81%)

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and increase in postoperative function (79%) over the same postoperative period ($p < 0.01$). At 3 months postoperatively, five (7%) participants demonstrated radiological sternal union and one (1%) participant was diagnosed with clinical sternal instability.

Conclusions A small magnitude of multi-planar motion at the sternal edges, at the mid-sternum, was demonstrated during dynamic upper limb and trunk tasks in a cohort of cardiac surgery patients post-sternotomy, over the first 3 postoperative months. Future research investigating motion at different levels of the sternum, with varying methods of sternal closure, and over a longer postoperative period is warranted to better inform sternal precautions and optimise postoperative recovery.

Keywords Cardiac surgery • Sternotomy • Ultrasound • Sternal precautions

Introduction

Worldwide, the median sternotomy remains the most commonly utilised incision in cardiac surgery [1,2]. Whilst the incidence of sternal complications in this population is relatively low (0.4–8%), it is associated with a comparatively high mortality rate (14–47%) [2,3]. In an attempt to reduce such complications, including sternal wound dehiscence, instability, infection and/or pain, all patients are routinely prescribed sternal precautions, restricting upper limb and trunk movements [3,4]. However, there is poor consensus amongst clinicians regarding what constitutes sternal precautions and limited evidence to support this practice [3,4]. Sternal precautions also pose a clinical dilemma in that they are contrary to routine exercises prescribed postoperatively to promote return to activities of daily living [3,4]. Further, the reinforcement of sternal precautions has been reported to delay independence in transfers and mobilisation, hospital discharge and functional recovery [3,4].

In the absence of in-vivo studies examining the effects of upper limb and trunk movements on sternal healing, current sternal precautions appear to have been predicated upon orthopaedic principles of fracture healing, as well as a limited number of biomechanical studies on cadaver/sternal replica models [1,5,6]. The orthopaedic literature reinforces the importance of optimal alignment and apposition of fracture sites [5]. Similarly, studies investigating sternal closure emphasise the importance of stability at the sternal edges [1,6]. In a foundational study, McGregor et al. (1999) postulated that sternal displacement > 0.20 cm may delay vascularisation and bone healing, whilst inter-fragmentary movement and osseous gaps < 0.20 cm may not be detrimental to bony healing [1]. However, the effects of upper limb and trunk movements on the healing sternum and, in particular, motion at the sternal edges following median sternotomy over time, are yet to be objectively measured. Few studies have also considered the impact upper limb and trunk movements have on anterior chest wall circulation, which may facilitate sternal healing, particularly in those undergoing internal mammary artery grafting [7].

Computed tomography (CT) and radiography remain the conventional methods of imaging utilised to screen and diagnose sternal complications, despite evidence to suggest poor sensitivity and specificity of both techniques [8,9]. More recently, ultrasound has been demonstrated as a clinically valid and reliable measure of motion at the sternal edges in patients following cardiac surgery via median sternotomy [10,11]. The primary aim of this study was to measure motion at the mid-sternum during dynamic upper limb and trunk tasks in patients following cardiac surgery via median sternotomy using ultrasound, over the first 3 postoperative months. The secondary aim was to explore the impact of cardiac surgery on sternal pain and functional recovery over the same postoperative period.

Materials and Methods

Ethics approval was obtained from the Royal Melbourne and Melbourne Private Hospitals (ID: HREC 2011.240), and all participants provided written, informed consent. Additionally, the study was registered in the Australian New Zealand Clinical Trial Registry (TRIAL REGISTRATION NUMBER: ACTRN12614000073606).

Participants were enrolled in this prospective, observational study if they had elective or emergency cardiac surgery via median sternotomy at the Royal Melbourne and Melbourne Private Hospitals, over a 12-month recruitment period. Participants were aged 18 years and/or over, operated on by one of four cardiothoracic surgeons, and underwent conventional sternal closure with a series of single 12–gauge stainless steel wires. Potential participants were excluded if they had insufficient English to provide informed consent and/or participate in testing, were deemed medically unstable, demonstrated impaired cognition or confusion, had a physical impairment preventing participation in testing and/or had undergone cardiopulmonary resuscitation postoperatively.

All participants received standard postoperative care, including education on institution-specific sternal precautions. The sternal precautions were delivered in both verbal and written formats by the usual treating physiotherapists, and recommended for the first 4 to 6 weeks postoperatively. They included education on limiting elevation of the upper limbs, encouraging bilateral use of the upper limbs if needed only, avoiding lifting objects five kilograms or greater, no pushing or pulling, supporting the sternal wound during coughing/sneezing, and avoiding driving (until approval from their cardiologist, or appropriate medical professional). Participants were also advised to not continue tasks and/or exercises that were painful, to rest as required, and focus on a gradual return to their pre-morbid level of function.

Outcome Measures

Motion at the Sternal Edges

Real-time imaging of the sternum was captured using a SonoSite M-Turbo ultrasound (SonoSite Australasia Pty Ltd, Belrose, NSW, Australia), via a linear array transducer (15-16 MHz). Motion at the sternal edges was measured using the linear calliper function of version 0.8.6 of the MicroDicom software program (MicroDicom, Sofia, Bulgaria). Specifically, each end of the calliper was positioned on the respective sternal edges to measure the amount of separation and/or overlap of the sternal edges in the lateral (coronal plane) and anterior-posterior (sagittal plane) directions in centimetres [10,12] (Figure 1).

Sternal Instability

Sternal instability was assessed using the modified Sternal Instability Scale (SIS). The modified SIS is a physical examination test, which has been demonstrated to be a clinically valid and reliable measure of sternal instability in patients following cardiac surgery via median sternotomy [13]. It involves manual palpation of the motion and/or separation at the sternal edges during dynamic movements of the upper limbs and trunk [13]. A grade of zero corresponds to a clinically stable sternum, while a grade of three corresponds to a completely separated and unstable sternum [13].

Sternal Pain

The Visual Analogue Scale (VAS) was used to measure sternal pain, with previous research demonstrating that it is both a clinically valid and reliable measure of postoperative pain [14]. Participants were required to rate the amount of sternal pain they were experiencing by placing a mark along a 100 mm line, with anchors indicating no pain and maximum pain at the left and the right of the line, respectively [15]. Each VAS score was measured to the nearest millimetre, with higher scores indicating higher levels of pain [15].

Functional Status

Postoperative functional status was measured using the Functional Difficulties Questionnaire (FDQ). This questionnaire is a clinically valid, reliable and responsive measure of functional status in patients following cardiac surgery via median sternotomy [16]. The questionnaire prompts participants to rate the difficulty they experience when completing a series of 13 functional tasks involving the upper limbs and trunk, on a scale similar to the VAS [16]. Specifically, participants are required to place a mark along a 10 cm line, with anchors indicating no difficulty and maximum difficulty at the left and right of the line, respectively [16]. Each of the VAS scores for the 13 functional tasks were measured to the nearest centimetre and combined to arrive at a total score out of 130 [16]. Participants with higher scores were interpreted to experience greater difficulty with functional tasks involving the upper limbs and trunk, whilst the opposite applied to lower scores [16].

Radiological Sternal Union

Radiological sternal union was defined as the presence of a continuum of cortical bone bridging the sternotomy, with no evident sternal separation and/or overlap in the lateral and anterior-posterior directions on ultrasound imaging. This definition was drawn from research on CT imaging of the sternum post-cardiac surgery via median sternotomy, as well as orthopaedic literature on the imaging of fracture healing in

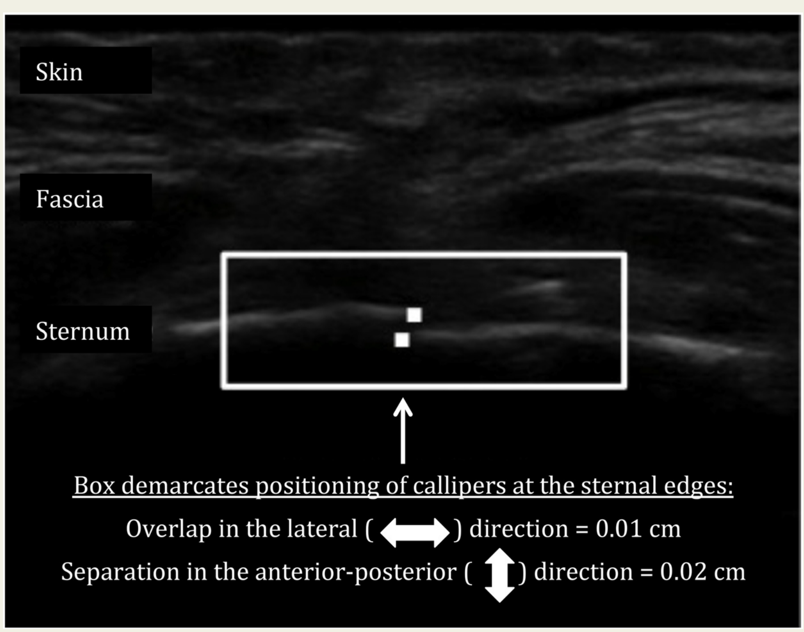

Figure 1 Sample ultrasound image of the sternum captured at rest depicting the overlap in the lateral direction and separation in the anterior-posterior direction of the sternal edges (cm).

long bones, which cites the non-existence of a gap at the fracture site as one of the factors contributing to radiological union [8,17].

Baseline data, including information on participant demographics (e.g. name, date of birth, etc.), as well as preoperative (e.g. past medical history, functional history, etc.), and hospital admission data (e.g. date of hospital admission and discharge, date and type of cardiac surgical procedure performed, etc.) data was also collected.

Testing Procedure

The study involved three testing sessions: 1) 3 to 7 days; 2) 6 weeks and 3) 3 months postoperatively. These sessions were standardised and conducted by a single physiotherapist (assessor) to minimise systematic errors of measurement [18]. The physiotherapist had more than 5 years of clinical experience and had received training in the novel method of ultrasound imaging of the sternum by a senior radiologist, researcher and cardiac surgeon.

Participants sat in a high-back chair, with their trunk supported and feet resting comfortably on the floor. The assessor initially graded the stability of the sternum using the modified SIS and asked participants to rate their sternal pain at rest using the VAS [13–15]. A single, two-dimensional ultrasound image was then captured at rest (baseline measure of motion at the sternal edges) and during five dynamic tasks involving the upper limbs and trunk including, deep inspiration, cough, unilateral and bilateral upper limb elevation and sit to stand. Video loops were also captured for descriptive purposes.

The ultrasound transducer was positioned directly onto the skin or hydrocolloid wound dressing over the sternum, at the level of the fourth intercostal space, to image the mid-sternal region (no external attachments were disturbed). The transducer was held in this position for the duration of each task to allow the assessor to scroll back and capture the optimal ultrasound image and maximum motion at the sternal edges. The pressure applied through the transducer was minimal, and participants were instructed to complete each task within their comfort levels to minimise patient burden. The order of task performance was randomised using a table of random numbers to minimise order effects [18]. Following the performance of each task, participants were again asked to rate their sternal pain using the VAS [14,15]. The FDQ was administered on completion of the ultrasound testing procedure [16]. The above process was repeated at each testing session.

Statistical Analysis

Sample Size

The sample size calculation was informed by a study conducted by El-Ansary et al (2007), which documented that the mean motion at the sternal edges in the lateral direction in participants diagnosed with chronic sternal instability (as measured at rest, in the seated position, approximately 4 years post-cardiac surgery) was 1.15 cm (standard deviation = 0.29 cm) [19]. Using a moderate effect size for a repeated measures analysis ($f = 0.25$), a sample size of 64 participants was calculated (power = 0.80; $p = 0.05$) [18]. The sample size was rounded up to 75 participants to account for a potential participant attrition rate of 15% [18].

Outcome Measure Analysis

Motion at the sternal edges and sternal pain were analysed using linear mixed models for within participant, non-parametric, repeated measures data [20]. This model was chosen as it considered participants lost to follow-up [20]. Additionally, it provided a useful approach for analysing longitudinal and repeated measures data, considering changes in outcome measures over time and the predictors of these changes [20]. No data imputation was undertaken. Each of the models included time and task as fixed effects, whilst the intercepts for participant, and participant and task were included as random effects [20]. Other factors considered, but not included in the linear mixed models were: 1) participant demographics; 2) pre, peri and postoperative data; and 3) task order. These factors were excluded upon examination of the Spearman's correlation coefficients, as they did not reveal a meaningful relationship with any of the outcome measures of interest (i.e. $p > 0.05$ and $r < |0.05|$) [20]. The final linear mixed models fit the assumptions of constant variance and normality of the residual values [20]. Functional status (FDQ) was analysed using Friedman's test for within participants, non-parametric, repeated measures data and Wilcoxon signed rank tests for post-hoc analysis [18].

Median and inter-quartile range (IQR) values were reported for non-parametric, continuous data, including age, motion at the sternal edges (lateral and anterior-posterior directions), sternal pain (VAS) and functional status (FDQ) [18]. Categorical data, including sex, co-morbidities and type of surgery were presented as percentages of the study sample [18].

Statistical analysis was undertaken using version 21.0 of the Statistical Package for the Social Sciences software program (IBM Corporation, New York, Armonk, NY, USA). The level of statistical significance was set at a $p < 0.05$ [18].

Results

Participant Demographics

259 patients were screened for eligibility in this study, of which 75 (29%) participants were enrolled (131 patients did not meet the inclusion criteria, 37 declined to participate and 16 were excluded for other reasons). Additionally, nine (12%) participants were lost to follow-up (two participants died, five declined to attend follow-up and two were unable to be contacted). A summary of participant enrolment and flow throughout the study is shown in Figure 2.

The median age of the study sample was 66 years (IQR = 56–77 years) and comprised of 43 (57%) males.

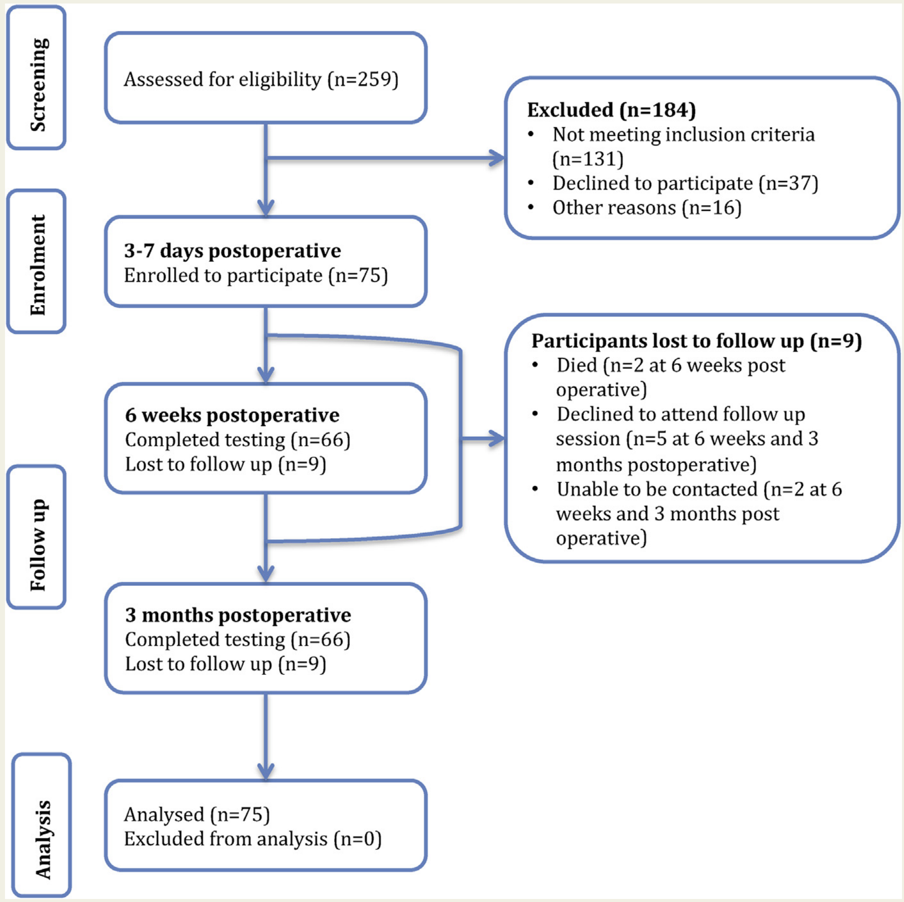

Figure 2 A summary of participant enrolment and flow throughout the study.

Forty-nine (49) (65%) participants underwent a coronary artery bypass graft procedure, and the remainder underwent cardiac valve repair/replacement surgery. All participants received a median sternotomy with conventional stainless steel wire closure, although the number of wires used varied according to surgeons' preference. While there were no adverse events resulting from the study, one (1%) participant developed sternal instability at time point two, which persisted at time point three (modified SIS = 2). A summary of baseline data, including participant demographics is described in Table 1.

Motion at the Sternal Edges

Lateral Motion at the Sternal Edges

There was a significant decrease in magnitude of overlap of the sternal edges in the lateral direction from: 1) 3 to 7 days to 6 weeks postoperatively of 0.01 cm ($p < 0.01$) and 2) 3 to 7 days to 3 months postoperatively of 0.01 cm ($p < 0.01$) (Figure 3; Appendix 1). Coughing, however, produced a significant increase in magnitude of separation of the sternal edges in the lateral direction, compared to rest and all other tasks, at each postoperative time point ($p < 0.01$). Between the cough task and rest, there was a mean increase in magnitude of separation of the sternal edges in the lateral direction of 0.01 cm ($p < 0.01$). Between the cough task and remaining tasks, the mean increase in magnitude of separation of the sternal edges in the lateral direction ranged from 0.01 to 0.02 cm ($p < 0.01$) (Figure 3; Appendix 1).

Anterior-posterior Motion at the Sternal Edges

There was a significant decrease in magnitude of separation of the sternal edges in the anterior-posterior direction between: 1) 3 to 7 days to 6weeks postoperatively of 0.01 cm ($p < 0.01$); 2) 3 to 7 days to 3 months postoperatively of 0.01 cm ($p < 0.01$) and 3) 6 weeks to 3 months postoperatively of 0.01 cm ($p < 0.01$) (Figure 4; Appendix 1).

Sternal Pain

There was a significant decrease in magnitude of sternal pain from: 1) 3 to 7 days to 6 weeks postoperatively of 18.50 mm ($p < 0.01$); 2) 3 to 7 days to 3 months postoperatively of 24.00 mm ($p < 0.01$) and 3) 6 weeks to 3 months postoperatively of 5.50 mm ($p < 0.01$) (Appendix 2). Furthermore, there was a significant difference in the magnitude of sternal pain between each task assessed, at each postoperative time point ($p < 0.01$) (Appendix 2). When compared to rest, coughing was considered the most painful task across all

Table 1 Summary of baseline data, including participant demographics.

Baseline data	Variables	Values[a]
Age (years)		66 (56-77)
Sex	Male	43 (57%)
	Female	32 (43%)
Co-morbidities	Chronic obstructive pulmonary disease	11 (15%)
	Osteoporosis	11 (15%)
	Diabetes mellitus	24 (32%)
	Obesity	14 (19%)
	Previous median sternotomy	3 (4%)
	Chronic cough	5 (7%)
	Smoking history	12 (16%)
Procedure	Coronary artery bypass graft	49 (65%)
	• Bilateral internal mammary artery graft	10 (13%)
	Cardiac valve repair/replacement	26 (35%)
	Postoperative mechanical ventilation >48 hours	18 (34%)
Attendance at outpatient cardiac rehabilitation program	Yes	46 (61%)
Compliance with at least one sternal precaution	Yes	
	• 5 to 7 days postoperatively	58 (77%)
	• 6 weeks postoperatively	35 (47%)
	• 3 months postoperatively	7 (9%)

[a]Values expressed as median (IQR) or frequency (percentage).

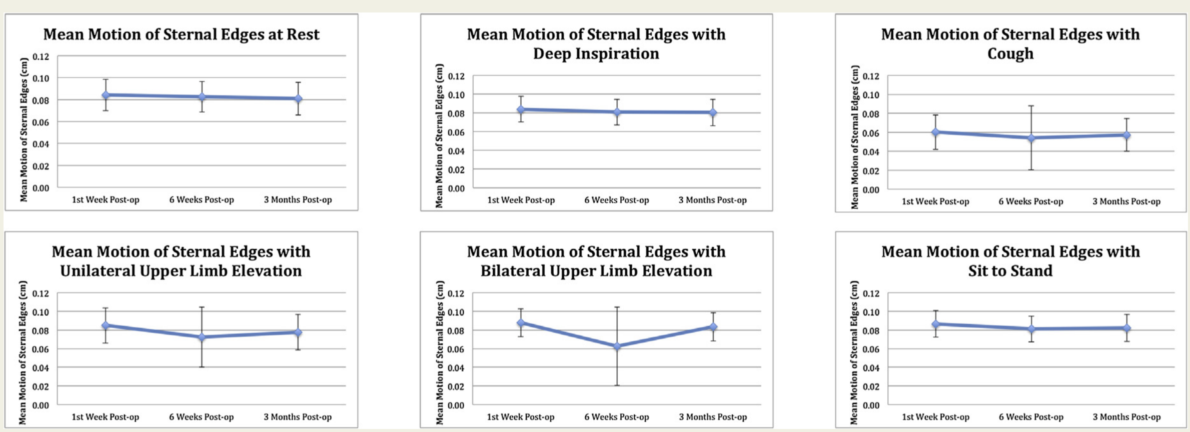

Figure 3 Changes in lateral mean motion at the sternal edges (cm) over the first 3 postoperative months at: 1) rest; 2) deep inspiration; 3) cough; 4) unilateral upper limb elevation; 5) bilateral upper limb elevation and 6) sit to stand (95% confidence interval bars included).

postoperative time points, followed by unilateral and bilateral upper limb elevation, sit to stand and deep inspiration ($p < 0.01$) (Appendix 2).

Functional Status

There was a significant increase in postoperative function over time ($p < 0.01$). Post-hoc analysis identified a significant increase from: 1) 3 to 7 days to 6 weeks postoperatively of 53% with FDQ scores decreasing from 48.80 to 23.10 cm ($p < 0.01$); 2) 3 to 7 days to 3 months postoperatively of 79% with FDQ scores decreasing from 48.80 to 10.10 cm ($p < 0.01$) and 3) 6 weeks to 3 months postoperatively of 57% with FDQ scores decreasing from 23.10 to 10.10 cm ($p < 0.01$).

Incidental Findings

All of the tasks assessed resulted in < 0.20 cm of motion at the sternal edges, at each postoperative time point. At 3 months postoperatively, nine (12%) participants demonstrated radiological sternal union at rest. Of these participants, only five (7%) demonstrated radiological sternal union on dynamic task assessment as well.

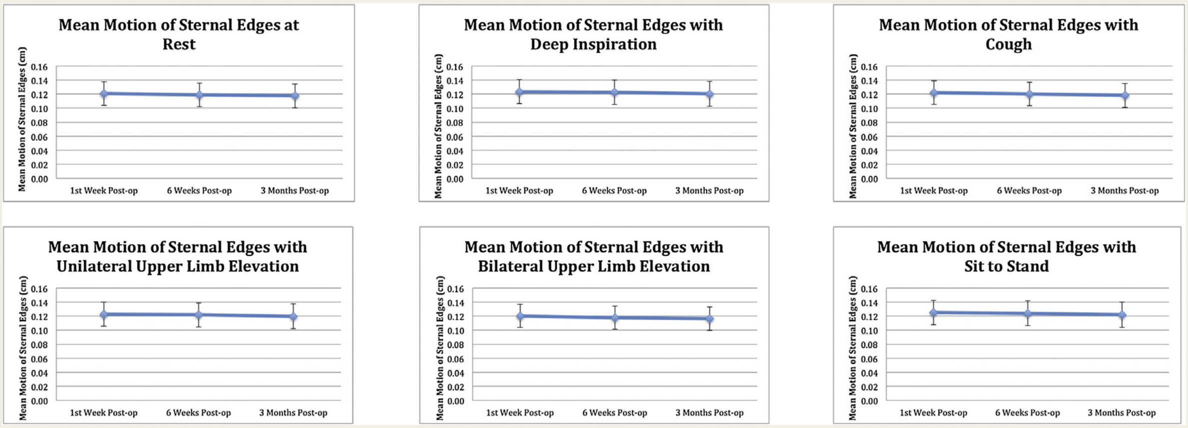

Figure 4 Changes in anterior-posterior mean motion at the sternal edges (cm) over the first 3 postoperative months at: 1) rest; 2) deep inspiration; 3) cough; 4) unilateral upper limb elevation; 5) bilateral upper limb elevation and 6) sit to stand (95% confidence interval bars included).

Discussion

This study is the first to report the effects of dynamic upper limb and trunk tasks that replicate those required in activities of daily living, but are restricted with the prescription of routine sternal precautions following cardiac surgery via median sternotomy. Specifically, the results of this study report that there is a small amount (< 0.20 cm) of multi-planar motion at the sternal edges during dynamic upper limb and trunk tasks, over the first 3 postoperative months. Based on the suggestions of Macgregor et al. (1999) that inter-fragmentary movement and osseous gaps < 0.20 cm may not be detrimental to bony healing, upper limb and trunk use may be considered safe following cardiac surgery via median sternotomy [1]. The results of this study also report a decrease in sternal pain and increase in functional recovery over time, with participants tolerating bilateral upper limb and trunk movements better than unilateral movements. Given that Sturgess et al. (2014) reported a significant improvement in sternal pain in participants who completed a thoracic exercise program over the first 6 weeks post-cardiac surgery, the early prescription of symmetrical upper limb and trunk exercises may be feasible and facilitate functional recovery in this patient population [21]. Based on these results, the authors suggest that placing restrictions on the use of upper limbs and trunk after cardiac surgery via median sternotomy in the form of routine sternal precautions may not be warranted in all patients. It may be more pertinent for future research to investigate individualised sternal precautions based on evidence-based risk factors for sternal complications [3].

Coughing produced the greatest magnitude of motion at the sternal edges, as well as sternal pain, at each postoperative time point. The motion at the sternal edges exhibited during coughing was a high velocity, multi-planar sheering movement (Appendix 3 - Video). This is consistent with previous studies that report coughing increases intra-thoracic pressures to 300 mmHg and imposes greater strain (up to 60 pounds) to the sternal closure than activities of daily living involving the upper limbs and trunk (5 to 22 pounds) [3,22]. Despite this, and evidence to dispute the role that deep inspiration and coughing play in the prevention of postoperative pulmonary complications in patients following cardiac surgery, coughing is still routinely encouraged postoperatively [23,24]. Given the low incidence of postoperative pulmonary complications following cardiac surgery, and the role that early mobilisation plays in reducing such complications, it may be more appropriate to encourage progression of mobilisation, rather than deep inspiration and coughing in this patient population [3,25]. Selected patients with persistent, non-productive and/or irritable coughs may also require a review of their medications [3].

While approximation of the sternal edges increased over time (i.e. there was a decrease in overlap of the sternal edges in the lateral direction and separation of the sternal edges in the anterior-posterior direction), the majority of participants failed to demonstrate radiological sternal union at the final time point. Bitkover et al. (1999) similarly reported that no participants demonstrated radiological sternal union on CT imaging, 3 months post-cardiac surgery using conventional stainless steel sternal closure, and only 50% demonstrated bony consolidation at 6 months postoperatively [8]. It was postulated that sternal healing continued beyond the first 3 postoperative months and that clinical sternal union occurred prior to radiological union. Of note, even fewer participants demonstrated radiological sternal union during dynamic tasks, when compared to rest, emphasising the importance of dynamic assessment. This study also provides specific osteokinematic insights. Motion in the lateral direction was dependent on the task assessed, suggesting that while motion at the sternal edges is multi-planar, movement in the lateral direction is more sensitive to upper limb and trunk movements. McGregor et al. (1999) similarly reported that a lower force was required to distract the sternal edges in the lateral, compared to the anterior-posterior direction [1]. This finding lends support to the application of sternal braces for patients at high risk and/or diagnosed with sternal instability as they promote approximation of the sternal edges in the lateral direction (e.g. Qualibreath) [3,26].

Strengths and Limitations

Ultrasound provides valuable real-time feedback regarding sternal healing in patients following cardiac surgery via median sternotomy. Specifically, it is a non-invasive, clinical tool that was well tolerated and facilitated monitoring of motion at the sternal edges, in all participants, in both the acute and community settings.

One of the limitations was the length of follow-up, with the results indicating that sternal healing continues beyond the first 3 postoperative months. Additionally, the authors conducted measures of mid-sternal motion, which may vary from motion at the manubrium/upper sternum where the ribs exhibit a ''pump-handle'' motion to increase the anterior-posterior diameter of the chest wall, and the lower sternum where the ribs move in a ''bucket-handle'' manner to increase the lateral diameter [27]. It must also be considered that, although the authors elected to investigate the most commonly used method of sternal closure with stainless steel wires, there are varying methods of sternal closure, and the current results may not be generalisable to these techniques. Future research should, therefore, follow up patients over a longer postoperative period, measure motion at the sternal edges along its entire length, and assess the impact of different sternal closure methods (e.g. enhanced adhesive sternal closure or sternal plating) on sternal healing. Lastly, there was the potential for observational bias given the type of study conducted, and the fact that a single assessor conducted and analysed the ultrasound testing and analysis.

Conclusions

This study measured mid-sternal motion at the sternal edges at rest and during dynamic tasks of the upper limbs and trunk in patients following cardiac surgery via median sternotomy, over the first 3 postoperative months, using ultrasound. While the majority of participants healed without sternal complications, the results suggested that a small magnitude of multi-planar motion at the sternal edges took place during all tasks over the first 3 postoperative months. Future research investigating motion along the sternal length with varying methods of sternal closure, and beyond the first 3 postoperative months is warranted to inform a precautionary rather than restrictive approach to sternal precautions that is based on individual assessment to optimise postoperative recovery.

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Conflicts of Interest

None.

Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.hlc.2018.05.195

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