

The effect of intracortical bone pin on shoulder kinematics during dynamic activities

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1 **The effect of intracortical bone pin on shoulder kinematics during** 2 **dynamic activities**

3 Intracortical bone pins are introduced as gold standard for analysing skeletal
4 motion because of eliminating soft tissue artefact. However, excluding this
5 methodological error might be in cost of intervening movement pattern by local
6 anaesthesia, pain and psychological effect of external tool within body. The
7 purpose of this study was to examine whether intracortical bone pins alter either
8 shoulder joint kinematics or coordination. Three subjects were analysed during
9 repetitions of arm elevation/depression in frontal and sagittal planes.
10 Retroreflective skin markers captured the motion in two sessions, before and after
11 inserting bone pins (SKIN and PIN sessions), respectively. Thoracohumeral and
12 scapulothoracic kinematics and scapulohumeral rhythm (SHR) were compared
13 between the two sessions. Thoracohumeral exhibited lower elevation and internal
14 rotation in PIN session especially close to maximum arm elevation. The highest
15 differences were observed for scapulothoracic kinematics, with higher retraction
16 during abduction as well as higher posterior tilt, lateral rotation and retraction
17 during flexion in PIN compared to SKIN. In addition, no systematic changes in
18 SHR between subjects was found. SHR was well reproduced by Subject 1 in
19 sagittal plane and by subject 2 in frontal plane. Subject 3 made use of kinematic
20 redundancy to alter SHR after inserting pins in both frontal and sagittal plane.
21 Statistically significant lower SHR in PIN session was observed over 87-100 % of
22 thoracohumeral elevation/depression cycle in frontal plane and over 25-61 % of
23 cycle in sagittal plane. Further studies should treat carefully toward the clinical
24 validity of shoulder joint kinematics after inserting the bone pins.

25 **Keywords:** Intracortical bone pins, Scapulohumeral rhythm, arm movement,
26 kinematics

27 **Introduction**

28 Retroreflective markers mounted on either skin or intracortical bone pins are used to
29 highly accurately capture shoulder motion and evaluate the shoulder dynamics (Fayad et
30 al. 2008a; Dal Maso et al. 2014). Skin-mounted markers are more commonly used
31 because of their non-invasiveness. However, the soft tissue artefact is an inevitable

1 component of the resulting kinematics (Maiwald et al. 2017). Several numerical and
2 experimental solutions have been suggested to reduce this artefact. Bone-anchored
3 markers have been introduced as an experimental methodology to overcome this major
4 issue. Its invasiveness explains both the limited number of studies and the small sample
5 size. While the direct movement of bones can be benefit for methodological and
6 validation studies (Cereatti et al. 2017), the use of pins is also accompanied with negative
7 aspects for clinical inference: local anesthesia for inserting pins, interference of pins in
8 the motion of muscles, tendons, or ligaments, painful movements with pins and
9 psychological effect of an external tool within body (Maiwald et al. 2017). Maiwald et
10 al. (2017) have previously looked at such effects on foot dynamics. Based on ground
11 reaction force, subjects tended to have less striking foot contacts after inserting pins. They
12 reported that gait pattern does not systematically change by implanting pins. Due to
13 different anatomy and mechanical structure of shoulder complexity, however, it might
14 exhibit dissimilar behavior compared to the foot.

15 The effect of bone pins could change the motion of scapulathoracic or glenohumeral
16 joints. Furthermore, the coordination between these joints can be altered as neurological
17 and psychological effect to stimulate similar motion for shoulder complex before and
18 after pin insertion. Scapulohumeral rhythm (SHR) represents any changes in
19 scapulathoracic/scapulohumeral movement and their coordination (Inman and Abbott
20 1944) While able-bodied subjects exhibited an average ratio of 2:1 for glenohumeral
21 against scapulothoracic motion in 2D static abduction position(Inman and Abbott 1944),
22 a large variability (range of 1.25 to 7.9) exists between subjects and studies when SHR is
23 calculated as the ratio of glenohumeral elevation to scapulothoracic upward rotation using
24 3D motion analysis system (Braman J. P. et al. 2009; Yoshizaki et al. 2009). The
25 variability results from the fact that these two angles are not coplanar. Moreover,

1 numerical instability may occur for low arm elevation. Recently, SHR has been calculated
2 as the ratio of the 3D glenohumeral joint contribution against the 3D scapulothoracic joint
3 contribution to the total arm elevation to overcome these issues (Robert-Lachaine et al.
4 2015). Nevertheless, altered biomechanics or stability associated with shoulder
5 dysfunction affects the SHR. (Warner et al. 1992; Kibler et al. 2002). For example, Fayad
6 et al. (2008b) showed lower SHR in patients with glenohumeral osteoarthritis or frozen
7 shoulder due to higher scapular lateral rotation. Similarly, patients with rotator cuff tear
8 increased the scapular contribution to arm elevation leading to lower SHR. Such strategy
9 has been considered as positive adaptation for individuals to reach higher function level
10 (Mell, LaScalza, Guffey, Ray, Maciejewski, Carpenter, Hughes, et al. 2005). Our
11 objective was to assess how inserting intracortical bone pin alters thoracohumeral and
12 scapulothoracic kinematics, as well as shoulder joint coordination.

13 **Methods**

14 Four healthy male subjects volunteered to participate this study. Experimental protocol is
15 fully described in Dal Maso et al. (2014). The inclusion criteria were no history of pain
16 or dysfunction in shoulder. All participants showed the ability of generating normal range
17 of motion by getting scores lower than 10.5 at the Disabilities of the Arm, Shoulder and
18 Hand (DASH) questionnaire (Hudak et al. 1996). The participants, called as S1, S2, S3,
19 S4 (32, 27, 41, 44 years old, 172, 165, 182, 177 cm, and 80, 57, 82, 115 kg, respectively)
20 signed an informed consent form being approved by the Karolinska Institute (Sweden)
21 and the Université de Montréal (Canada) ethics committees.

22 Data collection was performed in two sessions in a single day, for each participant. For
23 session 1 (SKIN), 22 skin markers were attached to the left clavicle (5), scapula (4),
24 humerus (7), and thorax (6) based on the model introduced by Jackson et al. (2012). Their
25 locations were previously marked on the skin with a pencil to replace them accurately if

1 they had to be removed during the surgery. For session 2 (PIN), three intercortical bone
2 pins were added (left clavicle, scapular spine and deltoid insertion). The insertion of pins
3 was performed by a surgeon, following local anesthesia (see Dal Maso et al. (2014) for
4 details). Pin locations were adjusted to avoid muscles, nerves and blood vessels as well
5 as any contact of pins with head, neck and skin markers during movements. Marker
6 trajectories were recorded using 18-camera VICON™ optoelectronic motion analysis
7 system (Oxford Metrics Ltd, Oxford, UK) at 300 Hz.

8 Anatomical and relaxed static positions were primarily recorded for each person per
9 session. Thereafter, each participant was asked to perform movements in SKIN session
10 and repeat these movements in PIN session. The movements included functional motion
11 tasks and main tasks. Functional motion tasks were arm flexion, rotation, and
12 circumduction performed in each session to find functional joint centers and axes. Main
13 tasks involved 10 trials of arm elevation/depression in frontal plane
14 (abduction/adduction) and sagittal plane (flexion/extension). In S4, the location of the
15 scapula's pin interfered with the skin markers which had to be repositioned more laterally.
16 The post-surgery skin markers on the scapula were quasi-collinear. This resulted in the
17 impossibility of accurate kinematics calculations. S4 data were removed.

18 The systems of coordinates and sequences were defined based on ISB recommendations
19 (Wu et al. 2005). For both SKIN and PIN sessions, thoracohumeral and scapulothoracic
20 kinematics as well as SHR according to Robert-Lachaine et al. (2015) algorithm were
21 calculated from the skin-mounted markers for all available trials of arm
22 elevation/depression in frontal and sagittal plane. To calculate SHR it is primarily
23 necessary to extract the contribution of each joint, as total arm elevation is comprised by
24 3D contribution of glenohumeral and scapulothoracic. The glenohumeral position is set
25 to its reference posture, and total arm elevation is recomputed to retrieve the

1 scapulothoracic contribution. There, the glenohumeral contribution is achieved by
2 subtracting the primary total arm elevation from the re-computed one (Robert-Lachaine
3 et al. 2015). Peak values for SHR were also reported for each subject, each task and each
4 session, separately. The effect of inserting bone pins on thoracohumeral and
5 scapulothoracic rotations was interpreted based on the observations for each individual.
6 Statistical analyses were performed only for SHR using the common range of motion in
7 thoracohumeral elevation for all the subjects: [10° to 108°] in frontal plane and [14° to
8 100°] in sagittal plane. The SHR was normalized to 50 points for arm elevation (1-50%
9 of the cycle) and 50 points for arm depression (51-100%). Then, non-parametric paired
10 t-tests using statistical parametric mapping (SPM) were implemented, during elevation
11 and depression separately, to determine whether any significant differences exist between
12 SKIN and PIN sessions. The open-source SPM1d toolbox (<http://www.spm1d.org>) in
13 MATLAB (R2018b, Mathworks Inc) was used for our SPM analysis.

14 **Results**

15 *Descriptive statistics*

16 *SI*: In frontal plane, this subject exhibited similar thoracohumeral kinematics in both
17 sessions except for the interval near maximum elevation. Lower elevation at this interval
18 led to lower range of motion (RoM) for the plane of elevation as well as axial rotation in
19 PIN session (Figure 1, Table 1). Scapulothoracic kinematics showed higher lateral
20 rotation and retraction in PIN session, while the subject produced lower RoM for
21 scapulothoracic in this session. In addition, SHR was higher in PIN session during its
22 whole available range of thoracohumeral elevation compared to SKIN session (Figure 2).
23 The maximum rhythm occurred at the maximum thoracohumeral elevation for SKIN
24 session compared to middle range of thoracohumeral elevation for PIN session during

1 arm elevation, and it was achieved at highest thoracohumeral elevation for both sessions
2 during arm depression (Table 2). In sagittal plane, the subject generated similar
3 thoracohumeral kinematics for both sessions, while he generated lower RoM for axial
4 rotation in PIN session. Scapulothoracic kinematics showed higher lateral rotation,
5 retraction and posterior tilting during PIN session. The pin insertion also led to lower
6 RoM for retraction of scapulothoracic joint. SHR showed similar pattern and values for
7 SKIN and PIN sessions. The SHR showed an increase during the whole elevation, where
8 the rate of change decreased after early phase of elevation (Figure 2, Table 2). In frontal
9 and sagittal planes, SHR was higher during elevation compared to depression for both
10 sessions (Figure 1, Table 1).

11 *S2*: In frontal plane, lower thoracohumeral elevation was observed in PIN session, which
12 was accompanied by higher external rotation and lower RoM in the plane of elevation.
13 scapulothoracic also reduced the RoM for lateral rotation in this session (Figure 1, Table
14 1). Similar trend was observed for SHR during both elevation and depression for the two
15 sessions (Figure 2). In sagittal plane, the elevation of thoracohumeral lowered, and the
16 subject generated lower RoM for axial rotation. Regarding scapulothoracic kinematics,
17 the posterior tilting increased, while the lateral rotation generated lower RoM in PIN
18 session. In addition, SHR was higher in SKIN session than PIN session. The pattern of
19 change in SHR showed some differences: SKIN session started with an increasing rate
20 for SHR, and started to decrease with lower rate in the middle of elevation range, whereas
21 the PIN session conserved the increasing rate for SHR during the whole elevation range
22 (Figure 2, Table 2). For both sessions, *S2* showed lower SHR for elevation compared to
23 depression (Figure 2).

24 *S3*: In frontal plane, scapulothoracic kinematics handled lower posterior tilt, higher lateral
25 rotation and lower retraction for PIN session. While the RoM for thoracohumeral

1 elevation altered slightly, the scapulothoracic increased its RoM in all three planes of
2 rotation after inserting pins (Figure 1, Table 1). Dramatically lower SHR was also
3 observed in PIN compared to SKIN session (Figure 2). The pattern of SHR did not either
4 follow similar patterns between two sessions. SHR was lower during elevation compared
5 to depression. In both sessions maximum SHR occurred at the highest values of
6 thoracohumeral elevation (Table 2). In sagittal plane, the subject increased
7 thoracohumeral elevation, scapulothoracic lateral rotation as well as its RoM, and
8 scapulothoracic retraction during PIN session (Figure 1, Table 1). The different pattern
9 for SHR was also observed for elevation/depression. An approximately constant rate in
10 SHR was handled for elevation/depression in SKIN session. However, an increase in SHR
11 with thoracohumeral elevation during early arm elevation was followed by a decrease at
12 higher elevations in PIN session. During depression the subject kept an approximately
13 constant SHR near to the end of depression followed by decreasing rate for lower
14 thoracohumeral elevations (Figure 2, Table 2).

15 ***Statistical parametric mapping***

16 The group mean and standard deviation plots showed some significant differences in SHR
17 between SKIN and PIN sessions. In frontal plane, higher SHR was observed in PIN
18 session at the end of depression phase, over 87-100 % of elevation/depression phase, *i.e.*
19 from 108° to 95.3° ($p=0.002$, Figure 3). In sagittal plane, lower SHR was achieved in
20 PIN session compared to SKIN session. However, lower SHR was just significant before
21 and after maximum elevation over 25-61 % of thoracohumeral elevation/depression, *i.e.*
22 from 57° to 100° during elevation and 100° to 91.4° during depression phase ($p=0.002$,
23 Figure 3).

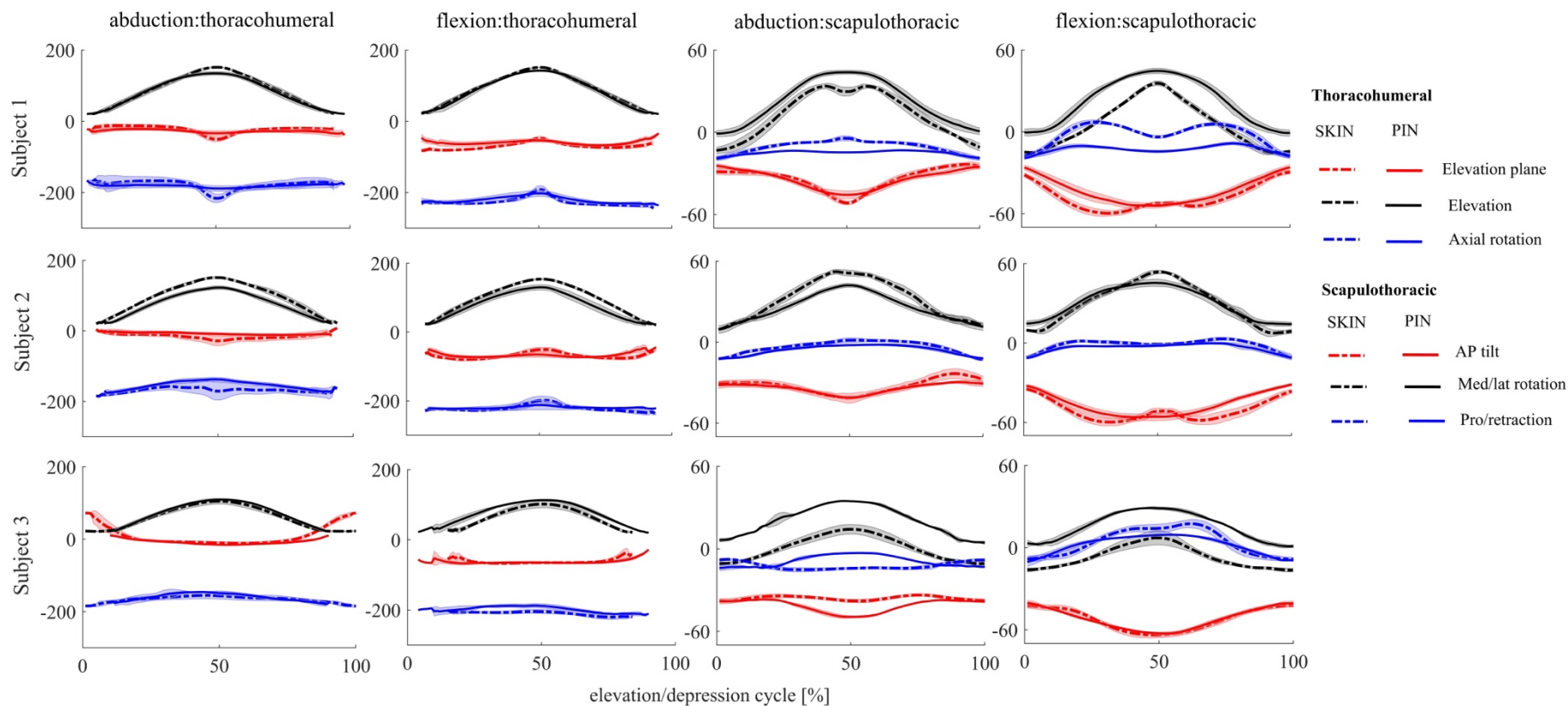
Table 1. Range of motion for thoracohumeral and scapulothoracic rotations during SKIN and PIN sessions

	Thoracohumeral		Scapulothoracic			
		Abduction [°]	Flexion [°]	Abduction [°]	Flexion [°]	
Subject 1	Plane of elevation	39.5±6.6	33.2±6.0	Anterior/Posterior tilt	28.4±1.2	30.9±2.6
		19.7±5.8	25.0±5.2		21.4±2.6	29.0±1.5
	Elevation/depression	130.5±1.4	129.6±2.1	Medial/Lateral rotation	48.4±2.9	51.9±1.7
Subject 2	Plane of elevation	113.9±4.7	121.4±2.4		45.2±3.4	46.4±3.3
		52.5±9.9	45.8±10.4	Protraction/retraction	14.8±2.1	25.6±1.5
	Elevation/depression	130.0±2.8	132.8±1.8		6.6±0.9	11.3±1.0
Subject 3	Plane of elevation	36.0±16.1	39.0±14.0	Anterior/Posterior tilt	19.1±4.0	26.2±2.4
		39.8±5.2	20.2±9.4		12.0±1.1	25.3±2.7
	Elevation/depression	130.0±2.8	132.8±1.8	Medial/Lateral rotation	43.1±1.9	47.1±2.1
Subject 3	Plane of elevation	99.0±4.8	110.7±5.8		32.9±3.9	32.3±2.4
		36.0±16.1	39.0±14.0	Protraction/retraction	14.8±1.5	14.8±1.3
	Elevation/depression	85.0±5.8	69.4±14.6		10.8±0.5	11.8±1.0
Subject 3	Plane of elevation	16.8±0.2	129.6±6.4	Anterior/Posterior tilt	5.7±1.0	18.6±3.8
		14.6±1.7	33.1±5.2		12.9±0.9	23.5±1.6
	Elevation/depression	85.0±5.8	69.4±14.6	Medial/Lateral rotation	20.4±0.9	19.7±7.8
Subject 3	Plane of elevation	89.5±2.2	92.2±3.0		30.3±0.7	28.3±0.3
		9.1±1.9	22.3±2.8	Protraction/retraction	5.4±0.4	23.9±3.4
	Elevation/depression	85.0±5.8	69.4±14.6		11.7±1.0	20.6±2.3

The range of motion is shown for three degrees of freedom of both thoracohumeral and scapulothoracic. For each degree of freedom, the first value (black) shows the SKIN session and the second value (blue) shows the PIN session.

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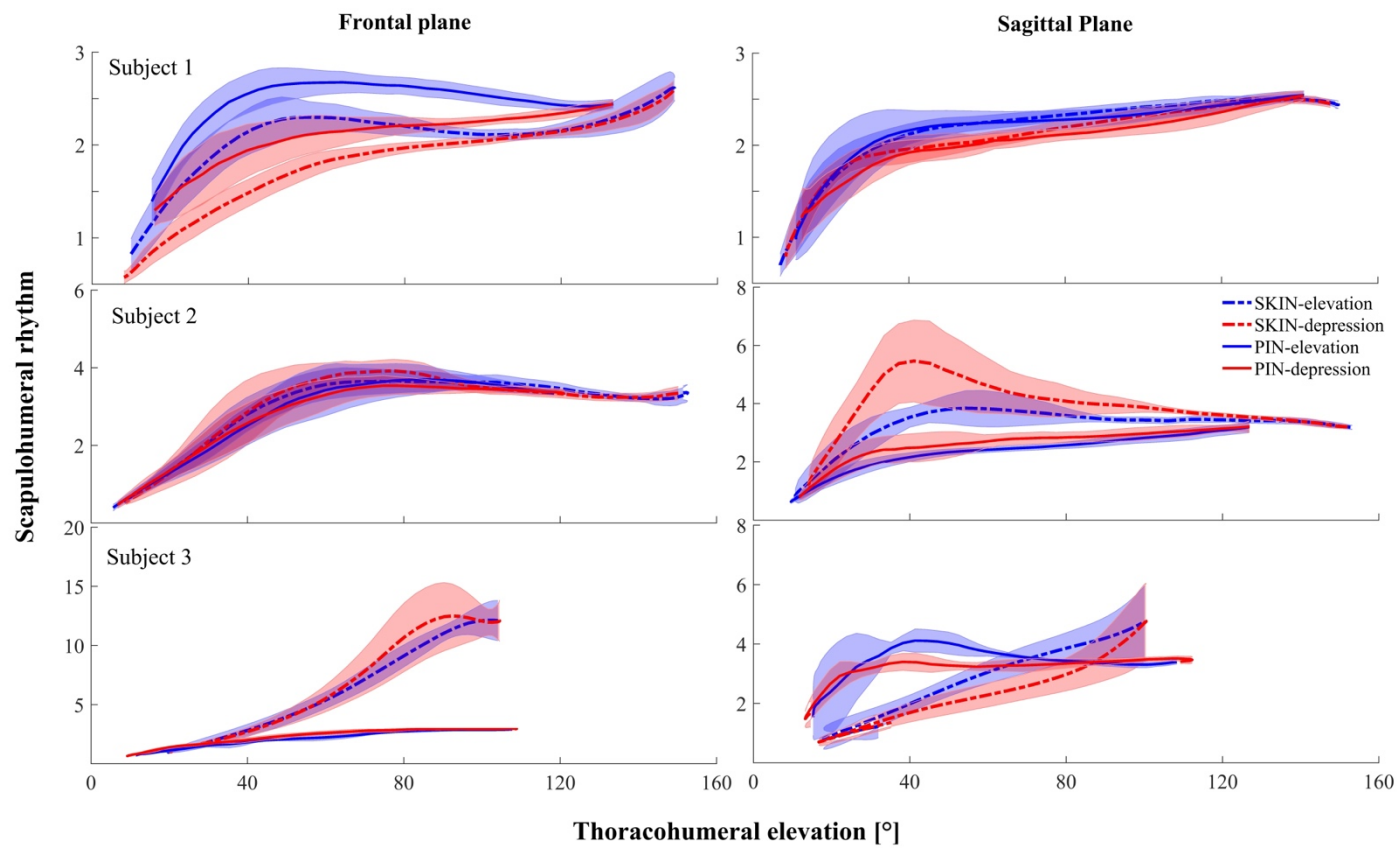
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2 Figure 1. Thoracohumeral and Scapulothoracic kinematics during arm elevation/depression in frontal plane (abduction) and sagittal plane (flexion)

3 for each subject. Dotted line show the SKIN session and filled line show the PIN session. Thick lines show the mean value and the shaded areas

4 show standard deviation. SKIN/PIN: session before/after bone pin insertion

5



1

2 Figure 2. Scapulohumeral rhythm during arm elevation/depression in frontal (left) and sagittal (right) plane. Blue shows elevation, red depression,
 3 dotted lines SKIN session, and filled lines PIN session. Thick lines show the mean value and the shaded areas show standard deviation. SKIN/PIN:
 4 session before/after bone pin insertion

1

2 Table 2. The maximum value of scapulohumeral rhythm and its corresponding thoracohumeral elevation during SKIN and PIN sessions

	Subject 1		Subject 2		Subject 3	
	SKIN	PIN	SKIN	PIN	SKIN	PIN
	maximum SHR (corresponding thoracohumeral elevation °)					
abduction	2.7 ± 0.2 (140.9 ± 31.9°)	2.7 ± 0.1 (65.3 ± 28.2°)	3.8 ± 0.3 (99.6 ± 35.2°)	3.8 ± 0.5 (82.2 ± 11.9°)	12.4 ± 1.6 (98.6 ± 5.0°)	2.9 ± 0.0 (98.5 ± 13.6°)
adduction	2.6 ± 0.1 (149.5 ± 2.5°)	2.4 ± 0.1 (126.4 ± 23.9°)	4.1 ± 0.4 (69.7 ± 8.5°)	3.6 ± 0.2 (86.3 ± 18.3°)	14.1 ± 1.2 (95.3 ± 3.8°)	3.0 ± 0.0 (108.3 ± 0.2°)
flexion	2.5 ± 0.0 (132.7 ± 6.8°)	2.6 ± 0.1 (140.5 ± 2.8°)	3.9 ± 0.6 (59.4 ± 22.8°)	3.2 ± 0.2 (125.9 ± 6.4°)	4.8 ± 1.1 (99.1 ± 10.9°)	4.2 ± 0.4 (38.8 ± 8.6°)
extension	2.5 ± 0.0 (134.6 ± 6.2°)	2.6 ± 0.1 (141.1 ± 3.3°)	5.9 ± 1.6 (44.4 ± 17.3°)	3.3 ± 0.2 (113.4 ± 32.5°)	4.8 ± 1.3 (100.8 ± 12.9°)	3.6 ± 0.1 (78.4 ± 39.0°)

abduction: elevation in frontal plane, adduction: depression in frontal plane, flexion: elevation in sagittal plane, extension: depression in sagittal plane.

All the values are reported as mean ± SD of all available trials for each task.

SKIN: session before bone pin insertion, PIN: session after bone pin insertion, SHR: scapulohumeral rhythm, SD: standard deviation

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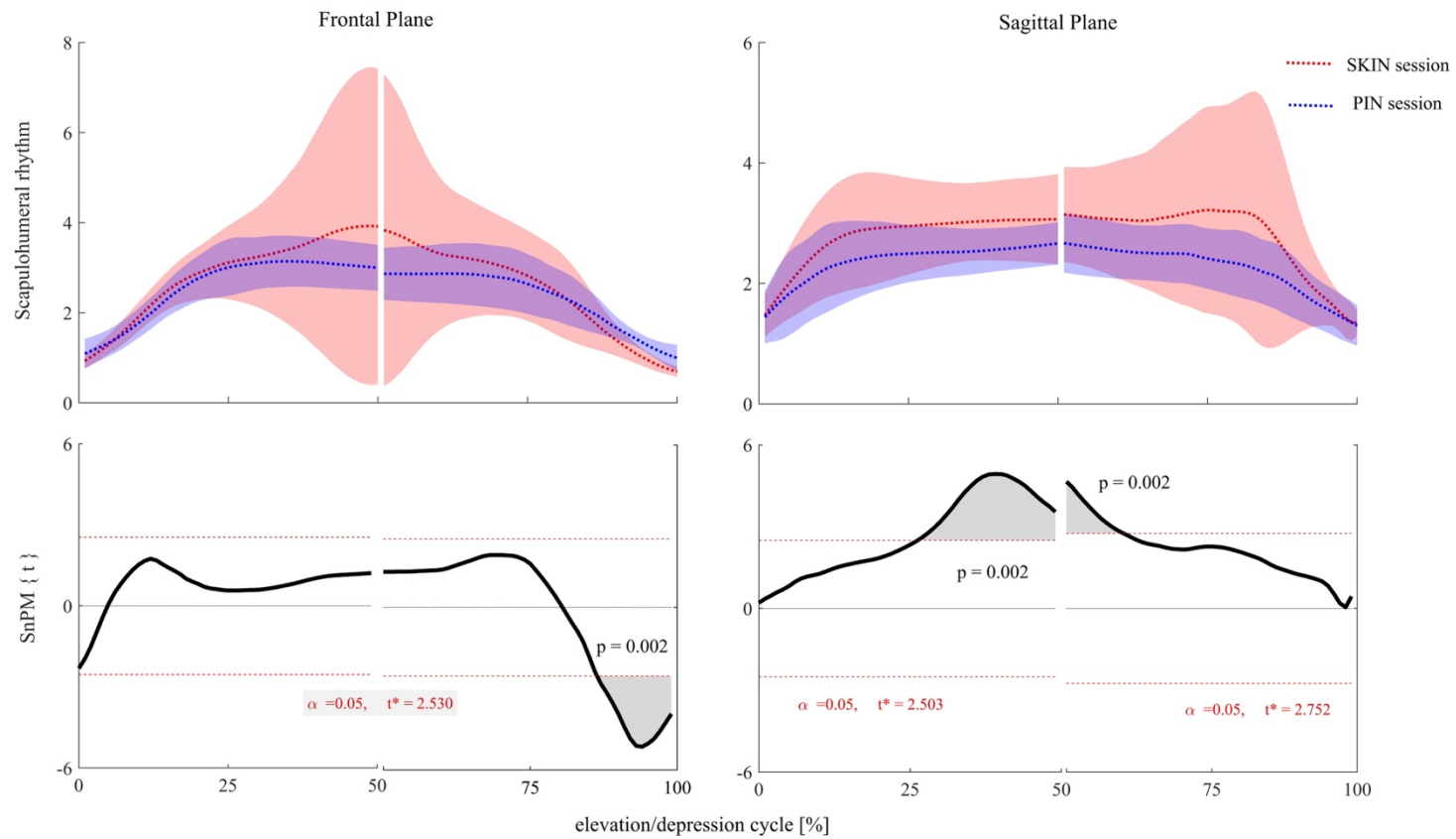
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2 Figure 3. Non-Parametric paired t-test analysis for comparing scapulohumeral rhythm during arm elevation/depression in frontal (left) and sagittal
 3 (right) plane. Red shows SKIN session and blue shows PIN session. Thick lines show the mean value and the shaded areas show standard deviation.

4 SKIN/PIN: session before/after bone pin insertion

1 **Discussion**

2 This study aimed to examine any changes in shoulder joint rotations and coordination as
3 a consequence of inserting intracortical bone pins during arm elevation/depression. The
4 results provide some insights on how bone pins may affect thoracohumeral and
5 scapulothoracic kinematics as well as SHR. After inserting shoulder bone pins,
6 thoracohumeral elevation and internal rotation as well as their RoMs changed during
7 abduction, especially close to the maximum arm elevation. More obvious differences
8 between PIN and SKIN sessions were observed for scapulothoracic kinematics during the
9 whole cycle of elevation/depression in both frontal and sagittal plane. In addition, SHR
10 also decreased in PIN session, *i.e.* less contribution of thoracohumeral joint and/or more
11 contribution of scapulothoracic joint to arm elevation based on our kinematics results.
12 However, SHR changes did not follow a systematic pattern across our participants. While
13 S1 and S2 could partially produce similar SHR during SKIN and PIN sessions, S3 failed
14 to generate similar values or patterns between sessions. S3 did not feel comfortable in
15 PIN session, and exhibited higher scapulothoracic rotations and RoMs, specifically
16 higher lateral rotation, after inserting pins. Due to kinematic redundancy, central nervous
17 system might have used different strategies to execute the motion. This might explain
18 different proportions of joint rotations after inserting pins for this subject. Based on our
19 observation, it is suggested that future clinical studies, that are going to consider the
20 kinematics from bone pins as gold standard, firstly identify and exclude the subjects who
21 exhibit obviously different biomechanical outcomes after inserting pins from further
22 statistical analysis. Although previous studies confirmed the validity of foot dynamics
23 calculated from intracortical bone pins comprising local anesthesia (Arndt et al. 2007;
24 Maiwald et al. 2017), we could not completely support this assumption for shoulder
25 coordination due to inter-subject variability. Here the inter-subject variability might be

1 referred to different sensitivity of subjects to the anesthesia and psychological effect of
2 holding pins during arm movements.

3 For all subjects, our results showed differences in scapulothoracic kinematics
4 (mediolateral rotation, anteroposterior tilting, and pro/retraction), while thoracohumeral
5 kinematics just altered slightly. In fact, the subjects reduced their axial rotation and the
6 plane of elevation after inserting pins. These alterations are consistent with findings of
7 previous studies about shoulder abnormalities. Mell, LaScalza, Guffey, Ray,
8 Maciejewski, Carpenter, Hughes (2005) showed increase in SHR due to higher scapular
9 motion for similar amount of humeral elevation in subjects with rotator cuff pathology.
10 McQuade and Smidt (1998) found that SHR might change as the effect of fatigue. Higher
11 mediolateral scapular rotation has also been mentioned to increase SHR in subjects with
12 frozen shoulder (Vermeulen et al. 2002; Lin et al. 2006). Therefore, it can be inferred that
13 inserting pins tend to alter scapulothoracic kinematics and SHR similar to
14 musculoskeletal disorders.

15 The changes in joint kinematics before and after pin insertion (Figure 1, Table 1) were
16 much higher than standard errors in measurement reported as [1.4° to 2.5°] for
17 scapulohumeral kinematics and [0.09° to 4.63°] for thoracohumeral kinematics during
18 arm elevation/depression in frontal and sagittal plane (Gonçalves et al. 2017). In order to
19 reduce the effect of skin motion artefact in the kinematic results for both session, an
20 advanced multibody kinematic models was used in this study, (Michaud et al. 2017)
21 which could decrease the error of thoracohumeral axial rotation to 5°, and scapula mis-
22 orientation to 14.9° compared to scapula palpatory as well as 1.1°<root mean square
23 error<3.3° for scapula kinematics compared to bone pins during arm flexion and
24 abduction.

1 In addition to joint rotations, SHR was selected to look at the effect of inserting bone pins,
2 since it can represent the movement quality index for shoulder complex for several
3 reasons. The most important reason is that kinematic redundancy enables the central
4 nervous system to generate a specific shoulder motion with different contribution of bony
5 structures (Yang et al. 2007; Fayad et al. 2008a). Patients with shoulder abnormalities
6 could alter the contribution of shoulder joints to provide stability and proper range of
7 motion thanks to such redundancy (Fayad et al. 2008a; Braman Jonathan P et al. 2009;
8 Forte et al. 2009). A further point is that SHR can be more robust than individual shoulder
9 joint kinematics due to involving less between-subject variability (McQuade and Smidt
10 1998). Additionally, in case of our study, the participants were not instructed to perform
11 maximum range of motion either before or after pin insertion; the same experimenter was
12 however in front of each participant to show each movement. This limits the comparison
13 above 108° of arm elevation. Due to the small sample size (n=3) in our cross-comparison
14 study, we compared the kinematics of each subject separately between SKIN and PIN
15 sessions. In addition, the obvious differences in SHR between subjects might be due to
16 individual movement strategies rather than different compensatory mechanisms. It is
17 recommended that validation studies which mount both skin markers and bone-pin
18 markers on the body estimate how they will interact with each other before data
19 collection. Otherwise, repositioning skin markers because of interference with bone pins
20 would deteriorate the kinematic results. In our study, one of our four available subjects
21 were excluded due to this issue. A well-organized protocol especially for such invasive
22 studies with small sample sizes will help in minimizing the between-subject differences
23 derived from methodological errors. While only kinematics was assessed in the present
24 study, electromyography and/or muscle force estimation may provide additional
25 information about the effect of pin insertion on the upper-limb biomechanics. However,

1 the estimation of muscle forces at the shoulder remains challenging due to co-contraction
2 and the complex trajectories of (multi-articular) muscles (Behm et al. 2003; De Sapio et
3 al. 2006). Some advanced algorithms are developed based on the tracking of both EMG
4 and kinematics which accounts for the excitation pattern of each individual (Pizzolato et
5 al. 2015; Bélaïse et al. 2018) . The effect of bone pins on muscle activations could then
6 be compared to the effect of soft tissue artefact as quantified by (Blache and Begon 2018).
7 Bone pin insertion and local anesthesia might alter the complementary action of
8 scapulothoracic and glenohumeral muscles to produce the complex kinematics and
9 rhythm during arm elevation/depression (Yoshizaki et al. 2009). Therefore, adding
10 muscle activation would improve the clinical benefits of such invasive studies.

11 **Conclusion**

12 Our results showed that inserting shoulder bone pins dominantly deteriorate the pattern
13 and range of motion of scapulothoracic joint rather than thoracohumeral joint. It was also
14 observed that scapulohumeral rhythm might be partially reproduced after pin insertion.
15 Eliminating methodological errors from soft tissue artifacts using intracortical pins would
16 not necessarily add more clinical value to the kinematic results, while the approach
17 remains relevant to model/algorithm validation.

18 **References**

- 19 Arndt A, Wolf P, Liu A, Nester C, Stacoff A, Jones R, Lundgren P, Lundberg A. 2007.
20 Intrinsic foot kinematics measured in vivo during the stance phase of slow running.
21 *Journal of biomechanics*. 40(12):2672-2678.
22 Behm DG, Power KE, Drinkwater EJ. 2003. Muscle activation is enhanced with multi-
23 and uni-articular bilateral versus unilateral contractions. *Canadian journal of applied*
24 *physiology*. 28(1):38-52.
25 Bélaïse C, Dal Maso F, Michaud B, Mombaur K, Begon MJMSD. 2018. An EMG-marker
26 tracking optimisation method for estimating muscle forces. 42(2):119-143.
27 Blache Y, Begon MJIToBE. 2018. Influence of shoulder kinematic estimate on joint and
28 muscle mechanics predicted by musculoskeletal model. 65(4):715-722.

1 Braman JP, Engel SC, LaPrade RF, Ludewig PM. 2009. In vivo assessment of
2 scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic
3 subjects. *J Shoulder Elbow Surg.* 18(6):960-967. eng.
4 Braman JP, Engel SC, LaPrade RF, Ludewig PM. 2009. In vivo assessment of
5 scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic
6 subjects. *Journal of Shoulder and Elbow Surgery.* 18(6):960-967.
7 Cereatti A, Bonci T, Akbarshahi M, Aminian K, Barré A, Begon M, Benoit DL,
8 Charbonnier C, Dal Maso F, Fantozzi S. 2017. Standardization proposal of soft tissue
9 artefact description for data sharing in human motion measurements. *Journal of*
10 *biomechanics.* 62:5-13.
11 Dal Maso F, Raison M, Lundberg A, Arndt A, Begon M. 2014. Coupling between 3D
12 displacements and rotations at the glenohumeral joint during dynamic tasks in healthy
13 participants. *Clinical Biomechanics.* 29(9):1048-1055.
14 De Sapio V, Warren J, Khatib O. 2006. Predicting reaching postures using a kinematically
15 constrained shoulder model. *Advances in robot kinematics.* Springer; p. 209-218.
16 Fayad F, Roby-Brami A, Yazbeck C, Hanneton S, Lefevre-Colau M-M, Gautheron V,
17 Poiraudau S, Revel M. 2008a. Three-dimensional scapular kinematics and
18 scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder.
19 *Journal of biomechanics.* 41(2):326-332.
20 Fayad F, Roby-Brami A, Yazbeck C, Hanneton S, Lefevre-Colau M-M, Gautheron V,
21 Poiraudau S, Revel M. 2008b. Three-dimensional scapular kinematics and
22 scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder.
23 *Journal of biomechanics.* 41(2):326-332.
24 Forte FC, de Castro MP, de Toledo JM, Ribeiro DC, Loss JF. 2009. Scapular kinematics
25 and scapulohumeral rhythm during resisted shoulder abduction—Implications for clinical
26 practice. *Physical Therapy in Sport.* 10(3):105-111.
27 Gonçalves D, Politti F, Bley A, Garbelotti S, Correa J, Lucareli PJG, Posture. 2017. Does
28 the assessor's experience matter when we evaluate the kinematics of the upper limb?
29 *Physical Therapy in Sport.* 10(3):105-111.
30 Hudak PL, Amadio PC, Bombardier C, Beaton D, Cole D, Davis A, Hawker G, Katz JN,
31 Makela M, Marx RG. 1996. Development of an upper extremity outcome measure: the
32 DASH (Disabilities of the Arm, Shoulder, and Hand). *American journal of industrial*
33 *medicine.* 29(6):602-608.
34 Inman VT, Abbott LC. 1944. Observations on the function of the shoulder joint. *JBJS.*
35 26(1):1-30.
36 Jackson M, Michaud B, Tétreault P, Begon M. 2012. Improvements in measuring
37 shoulder joint kinematics. *Journal of biomechanics.* 45(12):2180-2183.
38 Kibler WB, Uhl TL, Maddux JW, Brooks PV, Zeller B, McMullen J. 2002. Qualitative
39 clinical evaluation of scapular dysfunction: a reliability study. *Journal of Shoulder and*
40 *Elbow Surgery.* 11(6):550-556.
41 Lin Jj, Lim HK, Yang JL. 2006. Effect of shoulder tightness on glenohumeral translation,
42 scapular kinematics, and scapulohumeral rhythm in subjects with stiff shoulders. *Journal*
43 *of Orthopaedic Research.* 24(5):1044-1051.
44 Maiwald C, Arndt A, Nester C, Jones R, Lundberg A, Wolf P. 2017. The effect of
45 intracortical bone pin application on kinetics and tibioacaneal kinematics of walking
46 gait. *Gait & posture.* 52:129-134.
47 McQuade KJ, Smidt GL. 1998. Dynamic scapulohumeral rhythm: the effects of external
48 resistance during elevation of the arm in the scapular plane. *Journal of Orthopaedic &*
49 *Sports Physical Therapy.* 27(2):125-133.

1 Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE, Hughes RE. 2005.
2 Effect of rotator cuff pathology on shoulder rhythm. *Journal of Shoulder and Elbow*
3 *Surgery*. 14(1):S58-S64.
4 Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE, Hughes RE, JoS,
5 *Surgery* E. 2005. Effect of rotator cuff pathology on shoulder rhythm. 14(1):S58-S64.
6 Michaud B, Duprey S, Begon M. 2017. Scapular kinematic reconstruction—segmental
7 optimization, multibody optimization with open-loop or closed-loop chains: which one
8 should be preferred? *International Biomechanics*. 4(2):86-94.
9 Pizzolato C, Lloyd DG, Sartori M, Ceseracciu E, Besier TF, Fregly BJ, Reggiani MJ, Job.
10 2015. CEINMS: A toolbox to investigate the influence of different neural control
11 solutions on the prediction of muscle excitation and joint moments during dynamic motor
12 tasks. 48(14):3929-3936.
13 Robert-Lachaine X, Marion P, Godbout V, Bleau J, Begon M. 2015. Elucidating the
14 scapulo-humeral rhythm calculation: 3D joint contribution method. *Computer methods*
15 *in biomechanics and biomedical engineering*. 18(3):249-258.
16 Vermeulen H, Stokdijk M, Eilers P, Meskers C, Rozing P, Vlieland TV. 2002.
17 Measurement of three dimensional shoulder movement patterns with an electromagnetic
18 tracking device in patients with a frozen shoulder. *Annals of the rheumatic diseases*.
19 61(2):115-120.
20 Warner JJ, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. 1992. Scapulothoracic
21 Motion in Normal Shoulders and Shoulders With Glenohumeral Instability and
22 Impingement Syndrome A Study Using Moire Topographic Analysis. *Clinical*
23 *orthopaedics and related research*. 285:191-199.
24 Wu G, Van der Helm FC, Veeger HD, Makhsous M, Van Roy P, Anglin C, Nagels J,
25 Karduna AR, McQuade K, Wang X, Job. 2005. ISB recommendation on definitions of
26 joint coordinate systems of various joints for the reporting of human joint motion—Part
27 II: shoulder, elbow, wrist and hand. 38(5):981-992.
28 Yang J-F, Scholz JP, Latash ML. 2007. The role of kinematic redundancy in adaptation
29 of reaching. *Experimental brain research*. 176(1):54-69.
30 Yoshizaki K, Hamada J, Tamai K, Sahara R, Fujiwara T, Fujimoto T. 2009. Analysis of
31 the scapulohumeral rhythm and electromyography of the shoulder muscles during
32 elevation and lowering: comparison of dominant and nondominant shoulders. *Journal of*
33 *shoulder and elbow surgery*. 18(5):756-763.
34