

Accuracy and Reliability of a New Method of Measuring  
Three-Dimensional Scapular Kinematics

by

Douglas Allen Bourne

B.Sc. (Kinesiology) Simon Fraser University, 1994

B.Sc. (Physical Therapy) McGill University, 1997

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In

THE FACULTY OF GRADUATE STUDIES

School of Rehabilitation Sciences

We accept this thesis as conforming to the required standard

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The University of British Columbia

December 2003

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## **Abstract**

The shoulder is a very complex and mobile joint which relies on movement of the clavicle, scapula as well as the humerus. Measuring movement of the scapula is a problem that has plagued both researchers and clinicians alike. The scapula is a relatively flat bone that moves with considerable sliding under the skin, which makes it difficult to use skin markers to monitor its movement. The current gold standards for measuring scapular motion are invasive, involving the use of metal implants with or without radiation. The goal of this research was to develop and validate a non-invasive method to measure scapular movement. This new technique uses a grid of skin markers located over the scapula to monitor its movement. In addition, a patient-specific correction factor using digitization of bony landmarks was developed which takes into account skin movement.

The accuracy of this new method was determined using percutaneous bone pins as a gold standard. Eight university aged healthy subjects were recruited but the data from one subject had to be discarded due to pin loosening. An optoelectronic marker grid was applied to the skin overlying the scapula. Two 1.6mm bone pins with optoelectronic marker carriers were then inserted into the spine of the left scapula by an orthopaedic surgeon. During glenohumeral abduction, glenohumeral horizontal adduction, hand behind back, and forward reaching, three bony landmarks on the scapula were digitized at six arm positions to enable calculation of a subject-specific skin correction factor. The marker positions were recorded as the subjects performed each movement 10 times dynamically. The scapular movement from the bone pin method and the skin-based system were then compared.

The root mean square (rms) errors for the digitization of bony landmarks (which the skin correction factor depends on) were found to range between  $3.5^{\circ}$ - $4.6^{\circ}$ . The rms errors for the new skin-based technique were found to range between  $1.4^{\circ}$  -  $3.0^{\circ}$  when corrected with the subject-specific skin correction factor. Rms differences (reliability) between days ranged between  $3.8^{\circ}$  -  $7.5^{\circ}$ . A preliminary cadaver study showed that the pins have a small effect on skin movement.

Few studies have validated non-invasive measurement techniques of scapular motion using a gold standard. The rms errors of the new skin-based technique are equal to or less than currently available or reported methods. Therefore, it may be well suited to explore the role of scapular motion in shoulder pathologies.

## **Acknowledgements**

I would like to thank my wife Jacqueline. Without her love and support, this thesis would have never been possible.

I would also like to thank my co-supervisors, Dr. Tom Oxland and Dr. Donna MacIntyre. Working in Dr. Oxland's lab has been an amazing opportunity and I truly appreciate his guidance, feedback, and generosity. Dr. MacIntyre has done a great job making sure that I stay on track and providing a physiotherapy point of view to the research.

Anthony Choo not only started this project for his master's degree but was also instrumental in teaching me three-dimensional kinematics. Since I had not taken mathematics in over ten years, this was quite the feat. In addition he was always available to help with testing or to sound ideas off of.

I would like to thank Dr. Bill Regan who brought this research question to the Division of Orthopaedic Engineering Research and who took time off of his busy schedule to insert the bone pins in the subjects.

I would also like to thank Dr. Janice Eng for her understanding and help with statistics.

This research was funded by a PGS A scholarship from the National Sciences and Engineering Research Council of Canada.

I would like to thank everyone in the lab for their support whether it be helping with testing, discussing ideas, or helping me maintain my blood caffeine levels.

Finally but maybe most importantly, I would like to thank the volunteers to my study. It took plenty of courage to allow someone to drill metal pins into their shoulders. I am grateful for their trust and support.

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## **Chapter One: Introduction**

Shoulder problems are common in today's society and ranks second only to low back pain in clinical frequency (Mal and Costello, 2002; Sommerich *et al.*, 1993). The shoulder joint complex is very mobile and consists of the sternoclavicular, acromioclavicular, glenohumeral and scapulothoracic joints (Gray *et al.*, 1989). Movement of the humerus is accompanied by movement of the scapula and clavicle. Therefore measurement of both humeral and scapular motion is essential to understanding how the glenohumeral joint moves. If we better understood the movement at the glenohumeral joint we should gain insight into glenohumeral pathology.

The most difficult aspect of measuring this movement relates to the movement of the scapula. The scapula is a relatively flat bone which is positioned against the rib cage. When the scapula moves, there is considerable sliding underneath the skin. These facts make it difficult to use markers to monitor its position. The most accurate techniques for measuring scapular movements are invasive (Karduna *et al.*, 2001; Choo, 2001). This limits the research in this area and thus impairs our knowledge of shoulder movement.

Our current clinical assessment techniques cannot determine the amount of scapular movement. The most common techniques used clinically are either simple visual inspection as the subject moves (Watson, 2003), or a simple one dimensional measurement such as DiVeta's test or Kibler's lateral slide test (Kibler, 1991; Plotnikoff, 2001; DiVeta *et al.*, 1990). In addition there are various tests of scapular muscle strength and length (Kendall *et al.*, 1993; Sahrmann, 2002; Plotnikoff, 2001; Norkin and White, 1985; Daniels and Worthingham, 1986). Although not commonly used clinically, inclinometers can be used to

measure upward rotation of the scapula (Johnson *et al.*, 2001; Watson, 2003). Visual inspection is more subjective than objective, and the other measurements do not capture the three-dimensional movement of the scapula.

Besides being essential to measuring glenohumeral motion, scapular movement is widely believed to be an important factor in shoulder pathology (Borstad and Ludewig, 2002; Hebert *et al.*, 2002; Lukasiewicz *et al.*, 1999; Ludewig *et al.*, 1996; Ellen *et al.*, 2000; Mottram, 1997). Through the use of validated methods, we are starting to get an idea of how the scapula moves in subjects with shoulder pathology; however this relationship is still not fully understood. It is possible that abnormal scapular movement patterns contribute to pathology, or changes in scapular movement may just be a result or a response to shoulder pathology. An accurate, reliable, non-invasive technique would bridge clinical thought with scientific evidence.

Methods of measuring scapular motion can be broadly classified using three main characteristics. They are either invasive or non-invasive, either static or dynamic, and either two-dimensional or three-dimensional. Invasive techniques tend to be the gold standards and are often very accurate. Their invasiveness makes them difficult to use in a research environment and impossible in a clinical environment. Non-invasive techniques are usually more convenient to use but often lack the accuracy of invasive techniques. Some techniques can only measure scapular position in discrete static positions (Hebert *et al.*, 2000; Lukasiewicz *et al.*, 1999; Ludewig *et al.*, 1996) while others measure dynamically throughout a range (Karduna *et al.*, 2001). Two-dimensional techniques are becoming increasingly antiquated because they cannot measure the complex three-dimensional

movement of the scapula (de Groot, 1999). The ideal technique would be non-invasive, dynamic and three-dimensional.

Previous research addressing the biomechanics of the scapula has often involved either two-dimensional methods or static positions of the scapula (Hebert *et al.*, 2002; de Groot *et al.*, 1998; McQuade *et al.*, 1995; Barnett *et al.*, 1999; de Groot *et al.*, 1999; Inman *et al.*, 1996; Poppen and Walker, 1976).

Current research on non-invasive, three-dimensional techniques is focussed on three main areas. Several groups are looking at using digitized bony landmarks to measure scapular movement (Hebert *et al.*, 2002; de Groot *et al.*, 1998; McQuade *et al.*, 1995; Barnett *et al.*, 1999; de Groot *et al.*, 1999; Meskers *et al.*, 1998). The most common landmarks to use are the posterolateral acromion, the medial end of the scapular spine and the inferior angle. This technique is static since the subject holds a position while a device is used to digitize the landmarks. The accuracy of this method has not been examined.

Magnetic resonance imaging (MRI) is a promising technique since it is non-invasive and is able to directly measure the position of the relevant bones. MRI has a number of limitations. MRI is not currently able to measure dynamic movement. Subjects need to be motionless during scans. MRI is also very expensive. Finally, movement is restricted by the bulk of the magnets. Newer open magnet designs allow for a larger variety of movement but are still restrictive. Despite these limitations this technique has been used to successfully show differences in scapular position between subjects with shoulder instability and subjects with healthy shoulders (Eisenhart-Rothe R. *et al.*, 2003)

The other technique receiving attention is the use of an externally mounted electromagnetic marker to monitor scapular movement dynamically. There are fewer groups trying to develop these dynamic techniques (Karduna *et al.*, 2001; McQuade *et al.*, 1998) although its use is becoming more prevalent in the literature (Finley and Lee, 2003; Borstad and Ludewig, 2002; McQuade *et al.*, 1995; Johnson *et al.*, 2001; McQuade *et al.*, 1998; Karduna *et al.*, 2001). This electromagnetic marker technique has undergone some validation with a gold standard (Karduna *et al.*, 2001).

Mr. Anthony Choo (Ph.D. Student) and Dr. Tom Oxland (Director Orthopaedic Engineering Research at Vancouver Hospital and Health Sciences Centre) have developed a method of measuring scapular movement with a grid of skin markers (Choo, 2001). The three-dimensional positions of the markers are monitored with an optoelectronic camera system. Preliminary studies with a cadaver showed that this method has promise with most rotations having rms errors of less than 5°. The theory is that certain combinations of patches will be better at monitoring different rotations, i.e. markers along the length of the scapular spine may describe internal/external rotation well whereas more vertically-oriented markers would be better for monitoring anterior/posterior tipping.

As previously discussed, the problem with skin-based measurement systems is slippage of the bone under the skin. Ideally, a correction factor would be developed to counter this. A correction factor based on normative data would require large numbers of subjects to be involved in a study using one of the gold standards. Considering the invasiveness of the gold standards, this is not feasible. Normative data may not be generalizable to people with shoulder injuries. The optimal solution would be a correction factor based on the subject. If such a subject-specific correction factor could be formulated it should improve our accuracy..

## **1.1 Objectives**

The aim of this study was to develop a subject specific correction factor and to validate this new method of measuring scapular motion by comparing it to a gold standard. We chose optoelectronic markers mounted on bone pins as our gold standard because of their ability to dynamically measure scapular motion. The specific goals of this project were to:

1. To determine if bone pins significantly influence the orientation of the skin covering the scapula with respect to the scapula itself.
2. To use a gold standard (i.e. bone pins) to measure scapular motion during four different arm movements.
3. To assess the accuracy of digitizing bony landmarks to measure change in scapular position.
4. To assess the reliability and validity of a new non-invasive measure of dynamic scapular movement and patient specific skin correction factor.

## **1.2 Scope**

This study was limited to studying scapular motion in seven normal subjects. Bone pins were only used at one sitting and repeatability was measured for the skin based technique over two days. Four active humeral movements were tested. The study was restricted to rotations of the scapula. Translations of the scapula and rotations and translations of the clavicle were beyond the scope of this study. Although humerothoracic angles were calculated, they were only presented when scapular motion was normalized to motion of the humerus.

## **Chapter Two: Preliminary Cadaver Study**

### **2.1 Introduction**

In order to assess the accuracy of the new skin-based measurement technique we needed to compare it to a gold standard. The current gold standards for measuring scapular movement are invasive (Karduna *et al.*, 2001; Choo, 2001). They include roentgen stereophotogrammetric analysis (RSA) and the use of bone pins. RSA involves implanting small metal balls into the bones of interest and then using two x-ray machines to determine the exact location of each of the balls. This method is very accurate but is also invasive, involving surgery to implant the balls as well as exposing the subject to radiation. The use of bone pins involves placing thin metal pins under local anaesthesia such that they are secured in the bone of interest and are protruding out of the skin (McClure *et al.*, 2001).

Optoelectronic or electromagnetic sensors can be mounted on the exposed pins to monitor the movement.

Bone pins were selected as our gold standard over RSA for a number of reasons. Firstly, the pins are temporary. Once the experiment is done, the pins are removed. In RSA, the tantalum balls remain in the body after the experiment (Choo, 2001). Secondly, there is no radiation exposure with the bone pins. Thirdly, previous attempts at using RSA as a gold standard in our lab have failed because of inability to recruit patients. Finally, the bone pins can be monitored dynamically whereas RSA in our lab can only be monitored statically.

Bone pins have been used in another study to validate a skin based marker system for measuring scapular motion (Karduna *et al.*, 2001). They compared bone pins to an electromagnetic marker attached to the acromion, and to an electromagnetic marker attached

to a special jig mounted along the spine of the scapula. To validate the use of the bone pins they did two things. First, they calculated the force needed to bend the pins by the skin using beam theory. Second, they put bone pins in the scapula of a cadaver and measured the deflection in the pins while putting tension through the skin. They found negligible errors. Thus they validated that the pins did measure scapular motion but did not validate that the pins did not affect the movement of their markers by tethering the skin. We needed to ensure that the bone pins would not affect movement of our skin markers before using it as our gold standard.

The main objective of this preliminary cadaver study was to ensure that our gold standard did not affect skin motion. The use of a gold standard in a cadaver model provided the opportunity to explore a second objective concurrently. We were able to further validate the digitization method by determining its accuracy. Unfortunately, we could not completely validate these techniques with cadaver studies because of changes in tissue mechanics and the lack of active muscle activity. Because previous work has been conducted using bone pins to compare to a skin based assessment (Karduna *et al.*, 2001), it was hypothesised that the bone pins would not bias the movement of the skin under the markers.

## 2.2 Methods

An unembalmed cadaver was obtained from the University of British Columbia Anatomy Laboratory. The cadaver was placed on its left side and stabilized with sandbags. A 2.0mm k-wire was drilled into the L<sub>4</sub> vertebra of the cadaver and a four LED optoelectronic marker carrier was attached to the exposed pin. Another 2.0mm k-wire was drilled into the lateral epicondyle of the right humerus and another optoelectronic marker carrier was attached to

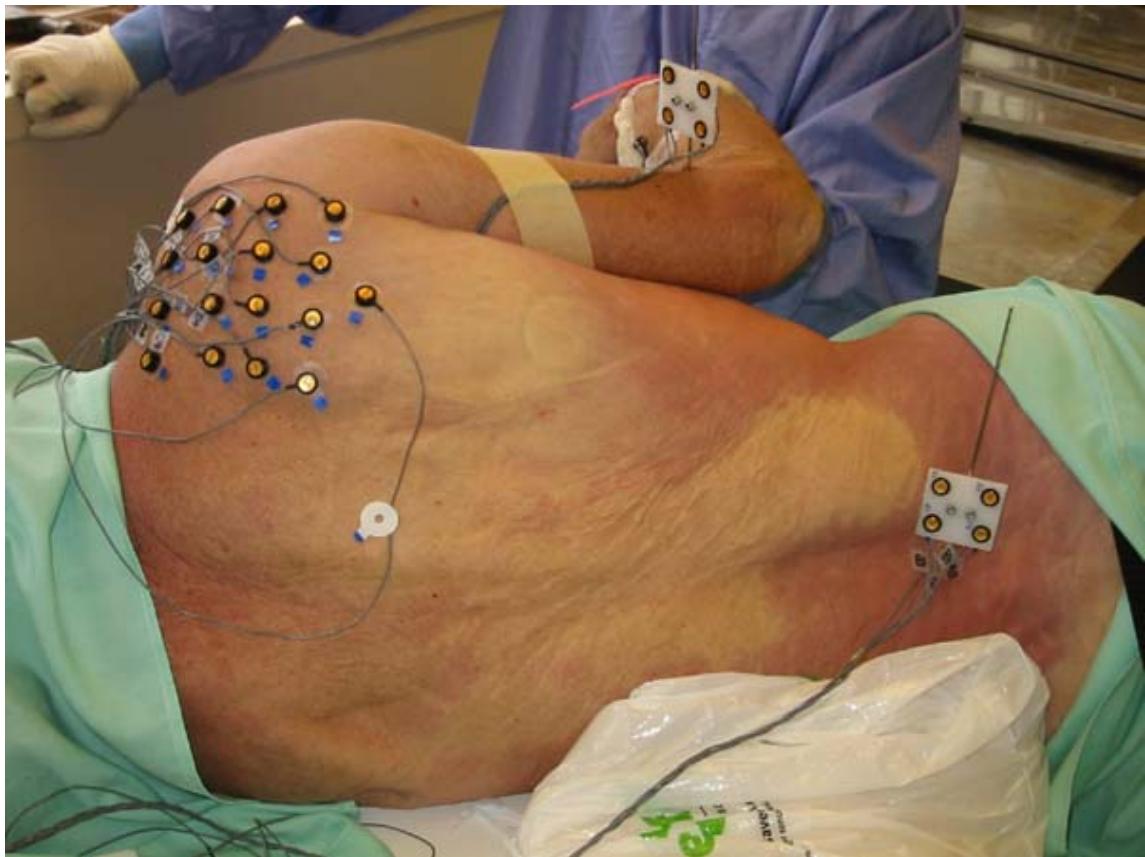
the exposed pin. Sixteen optoelectronic sensors were attached with electrode tape to the skin covering the scapula in a 4x4 grid pattern, with each marker 3cm away from its nearest neighbours. A seventeenth marker was placed just below the middle of the last row (Figure 2-1).

The cadaver's arm was put through a full range of glenohumeral flexion ten times. Movement of all markers was recorded continuously throughout the movement using an optoelectronic camera system [Optotrak 3020, Northern Digital, Waterloo, ON]. Movement was paced by an electronic metronome such that it took three seconds to reach end of range and three seconds to return. Practice trials were performed before recording. This served to precondition the cadaver as well as ensure correct timing.

An attempt was made to drill the bone pins into the lateral aspect of the acromion. This attempt failed as the pins tended to break through either the superior or inferior aspect of the acromion. Therefore, the bone pins were inserted in the scapula of the cadaver along the scapular spine close to the acromion (Figure 2-2). The medial pin was non-threaded and the lateral pin was threaded. In previous work completed in this lab (Choo, 2001), the far lateral scapular spine was found to be an unreliable location for skin markers due to skin deformation from the deltoid. The pins were placed as far lateral as possible while still allowing us to palpate the posterolateral acromion. Because we would not be placing skin markers at this location in live subjects, the bone pins should have less interference with the markers.

At four different positions (0%, 33%, 66% and 100% of full range of motion), three bony landmarks were digitized using the Optoelectronic camera system. The 0% position was

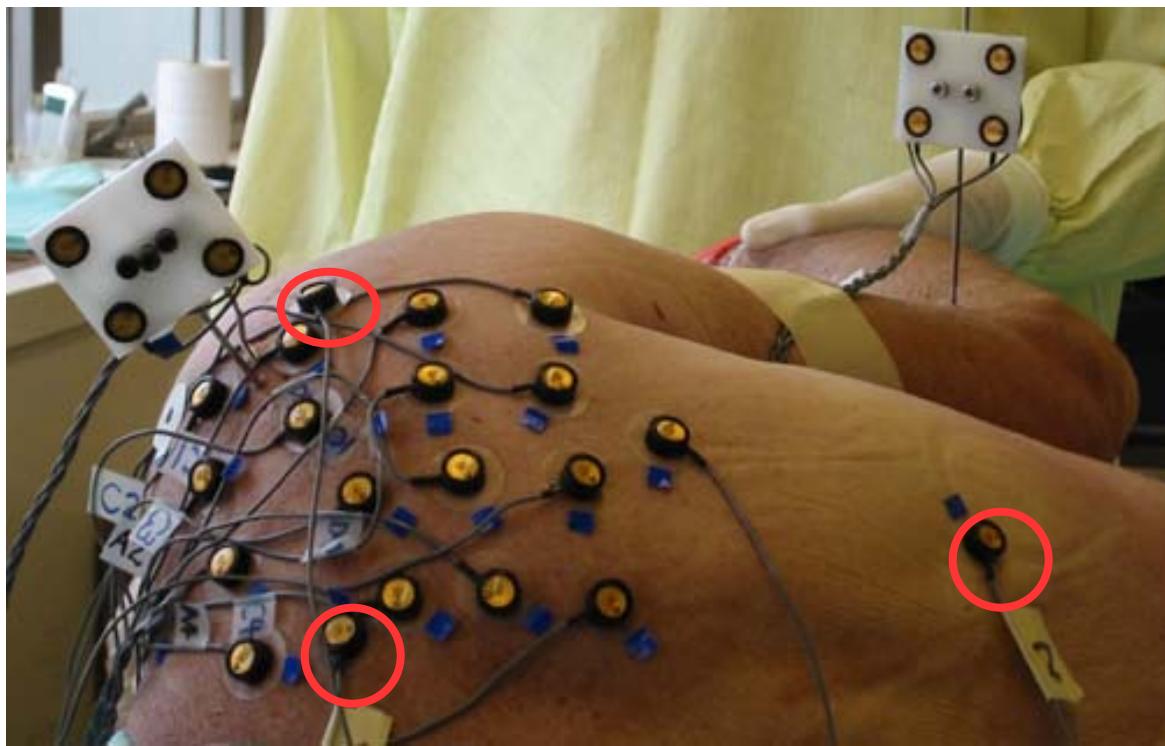
measured using the Optotrak probe using Northern Digital's "Digitize" program. This is the standard method for digitizing the reference position. Two different methods were used to digitize the landmarks for the 33%, 66%, and 100% positions. In method one, optoelectronic markers were attached to the landmarks using electrode tape (Figure 2-2). In method two, the Optotrak probe was used but the data was collected using Northern Digital's "Collect" program. The landmarks digitized were the medial inferior tip of the scapular spine, the posterior lateral corner of the acromion and the inferior angle of the scapula.



**Figure 2-1** Cadaver with optoelectronic marker grid over the scapula and marker carriers mounted on bone pins in the humerus and the lumbar spine.

The cadaver's arm was then flexed again ten times while being recorded by the optoelectronic camera system at 30Hz. At the end of the experiment the pins and markers were removed from the cadaver.

Movement of the skin markers before and after the bone pin placement were compared to make sure that the bone pins did not influence movement of the skin markers. A detailed description of reference frames, Euler angle sequences and data processing is given in the data analysis section.



**Figure 2-2** Cadaver with marker carrier mounted on bone pins drilled into the scapula. The circled optoelectronic markers were used for the digitization process.

It was proposed a priori that the use of bone pins would be deemed acceptable if the rms error between the skin markers with and without bone pins was less than  $5^\circ$  through a range of flexion of about  $135^\circ$ . This number was chosen because it allowed for some variation

between the trials while keeping the actual effect of the pins below 5°. Even though bone pins have been used as a gold standard for the scapula previously, it was important to verify the validity because our non-invasive technique was different from techniques used in previous studies (Karduna *et al.*, 2001). Furthermore, some locations of skin markers may be more sensitive to securing the skin to the scapula by the bone pins.

### **2.2.1 Data Analysis**

The Optotrak system calculates the three dimensional position of all of the markers and digitized points. These data were then imported into Matlab for further processing with a custom Matlab script. The equations described in Soderkvist and Wedin (Soderkvist and Wedin, 1993) were followed to calculate transformation matrices. A transformation matrix is a four-by-four grid of numbers which represents the change in orientation and position of an object with respect to the global reference frame. The next step was to convert the transformation matrices from a global reference frame to an anatomic reference frame. This step was needed to provide anatomically meaningful data. For example, it is more relevant to know the position of the scapula with reference to the thorax than it is to know the position of the scapula with respect to the chair. To convert these transformation matrices to an anatomical reference frame, the Matlab script used the landmarks digitized at the beginning of this study (not the landmarks digitized for the patient-specific correction factor).

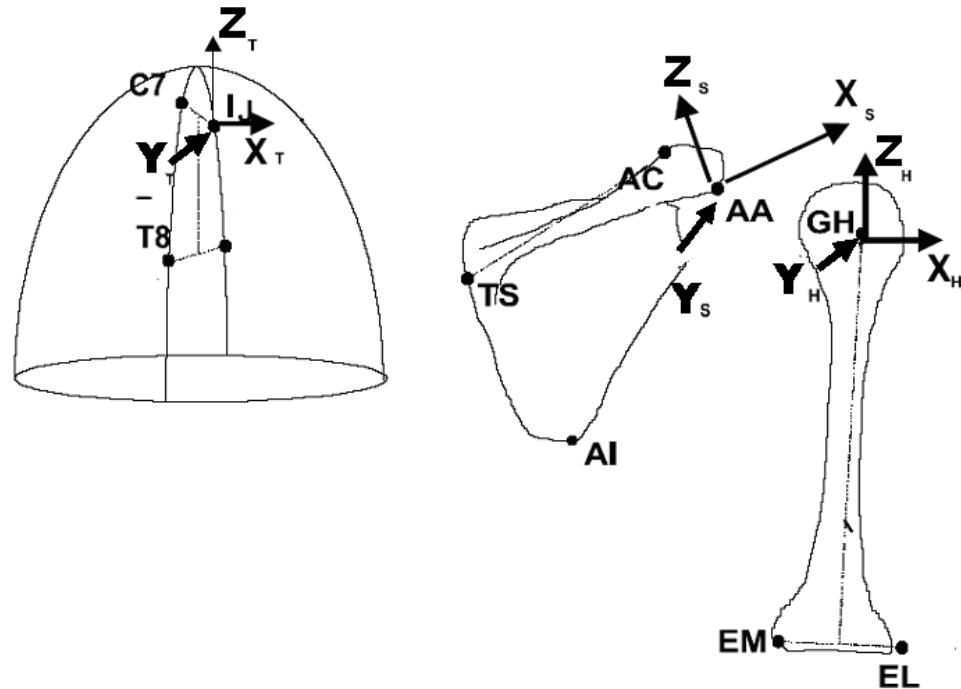
The coordinate systems were defined as follows (Figure 2-3). The Z axis of the thorax ( $Z_T$ ) was calculated as the vector from the spinous process of T7 to the spinous process of C7. The X axis of the thorax ( $X_T$ ) was perpendicular to the plane formed by C7, T7 and the sternal notch. The Y axis ( $Y_T$ ) was defined as the cross product of the Z and X axis. The X

axis for the scapula ( $X_S$ ) was calculated as the vector originating at the root of the scapular spine and ending at the posterolateral acromion. The Y axis of the scapula ( $Y_S$ ) was calculated as the vector perpendicular to the plane formed by the root of the scapular spine, the posterolateral acromion and the inferior angle of the scapula. The Z axis of the scapula ( $Z_S$ ) was calculated as the cross product between the  $X_S$  axis and the  $Y_S$  axis. Finally the reference frame for the humerus was defined as follows. The Z axis of the humerus ( $Z_H$ ) was calculated as the vector starting at the midpoint between the lateral and medial epicondyles and ending at the center of the head of the humerus. The center of the head of the humerus was calculated using a least squared algorithm (Gamage and Lasenby, 2002). The Y axis of the humerus ( $Y_H$ ) was calculated as the vector perpendicular to the plane formed by the head of the humerus, the medial epicondyle and the lateral epicondyle. The X axis of the humerus ( $X_H$ ) was calculated as the cross product between the  $Y_S$  and  $Z_S$  axis. These reference frames are the similar to those recommended by the International Shoulder Group of the International Society of Biomechanics (van der Helm, 2002) except that they used T8 instead of T7 and the Y axis was vertical instead of the Z axis.

Although transformation matrices are mathematically a very robust way of representing rotational and translational data, they are not very intuitive. In order to make the data easier to interpret, it was represented as the Euler angle sequences (in degrees) between the distal (humerus or scapula) and proximal (scapula or thorax) segments. Euler angles are a sequence of three rotations which are calculated from the transformation matrix.

The Euler angle sequence used for the humerus with respect to the thorax was  $Z_H$ , followed by  $Y'_H$ , followed by  $Z''_H$ , the amount of internal/external rotation.  $Z_H$  describes the rotation to bring the  $Y_H$  axis perpendicular to the plane of elevation.  $Y'_H$  describes the amount of

elevation and  $Z''_H$  describes the amount of internal/external rotation. The Euler angle sequence used for the scapula with respect to the thorax was  $X_s$ , posterior/anterior tilting, followed by  $Y_s$ 's, upward/downward rotation, followed by  $Z''_s$ , internal/external rotation.



**Figure 2-3** Reference frames for this study. Modified from the International Shoulder Group of the International Society of Biomechanics (van der Helm, 2002). C7: spinous process of the seventh cervical vertebrae. T8: spinous process of the eighth thoracic vertebrae. IJ: sternal notch. TS: medial root of scapular spine. IA: inferior angle of scapula. AC: acromioclavicular joint. AA: posterolateral acromion. GH: center of glenohumeral head. EM: medial epicondyle. EL: lateral epicondyle.

These Euler angle rotation sequences were calculated for the bone pins, skin marker grid, as well as for the bony landmark digitization method. An rms error was calculated for the skin marker grid before and after pin insertion. An rms error was also calculated between the pin markers and the digitization method.

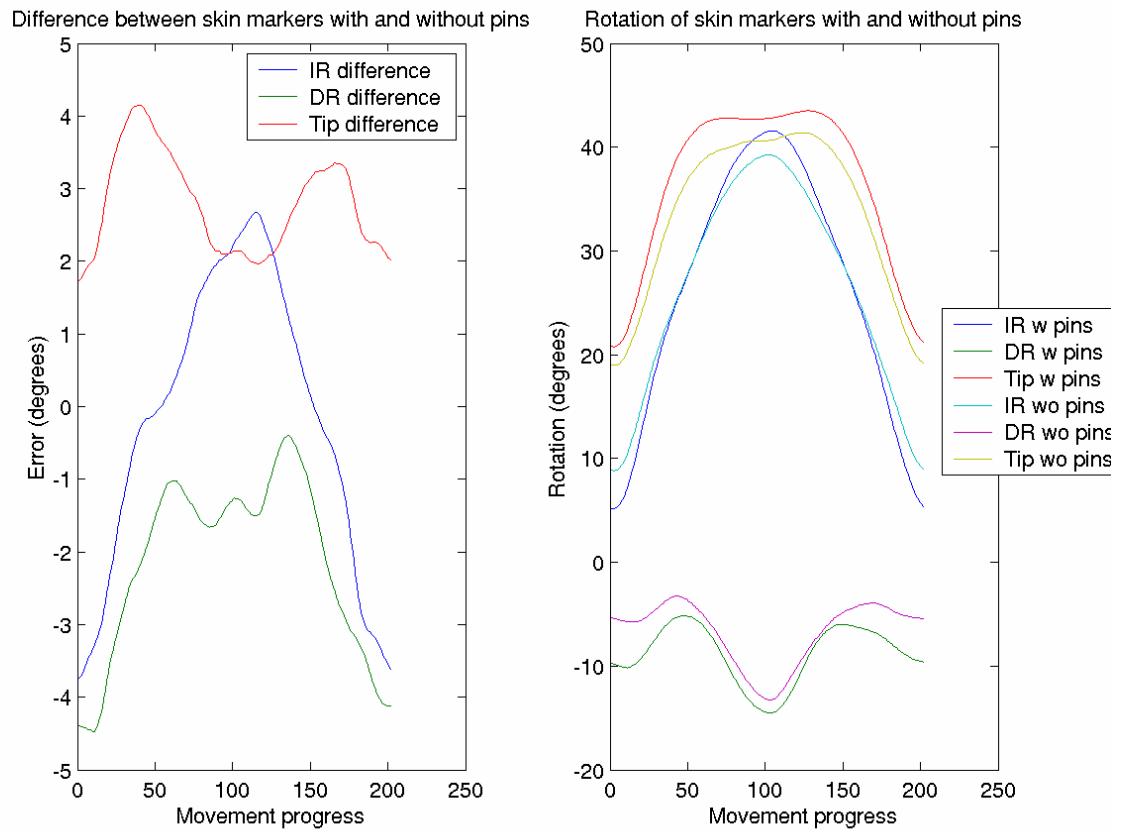
## **2.3 Results**

### **2.3.1 General Observations**

The threaded pins pulled the skin up the threads thus raising the skin. The threaded pin used on the scapula was placed more lateral to minimize any effect this would have. As stated in the methods, an attempt was made to insert the pins in the lateral aspect of the acromion, but failed because the pins tended to break through either the superior or inferior aspect of the acromion. The pins were easily inserted into the lateral scapular spine. The process of inserting the pins slightly moved the scapula. Since the cadaver lacked normal muscle tone the scapula did not return to the same resting position. This made it difficult to assess the exact effect of the bone pins.

### **2.3.2 Effect of Bone Pins on Skin Markers**

A common pattern became apparent upon comparison of the skin markers with and without the bone pins. The difference was greatest at the start of the movement and decreased as the arm was flexed (Figure 2-4). The overall difference between the markers with the pins and without was always less than  $5^\circ$ . This decreased to  $1^\circ$  or  $2^\circ$  at the peak of movement. The results were acceptable with a difference of  $1^\circ$  to  $2^\circ$  for scapular tipping,  $1.5^\circ$  to  $3.5^\circ$  for downward rotation and  $2.8^\circ$  to  $4.3^\circ$  for internal rotation (Table 2-1). If the difference at the start of movement was taken into account the results were improved with a difference of  $1^\circ$  to  $4^\circ$  for scapular tipping,  $1^\circ$  to  $2.5^\circ$  for downward rotation and  $0.7^\circ$  to  $1.8^\circ$  for internal rotation (Table 2-2)



**Figure 2-4** Difference between patch movement with pins and without. The graph on the left shows the difference between the movements. The graph on the right shows the actual movements. IR internal rotation, DR downward rotation, Tip scapular tipping. w: with, wo: without.

**Table 2-1** Overall rms differences between the skin markers with and without pins. Each row represents a different patch or grouping of markers.

Patch	Tipping	Downward Rotation	Internal Rotation
1	1.0	3.3	4.2
2	0.9	2.3	4.2
3	2.0	2.4	2.9
4	1.6	2.3	3.4
5	2.0	2.3	3.8
6	1.1	1.5	4.0
7	1.2	2.6	4.0
8	1.3	2.8	4.3
9	1.3	3.5	3.0
10	1.3	2.8	4.3

**Table 2-2** Overall rms differences between the skin markers with and without pins taking offset into consideration. Each row represents a different patch or grouping of markers

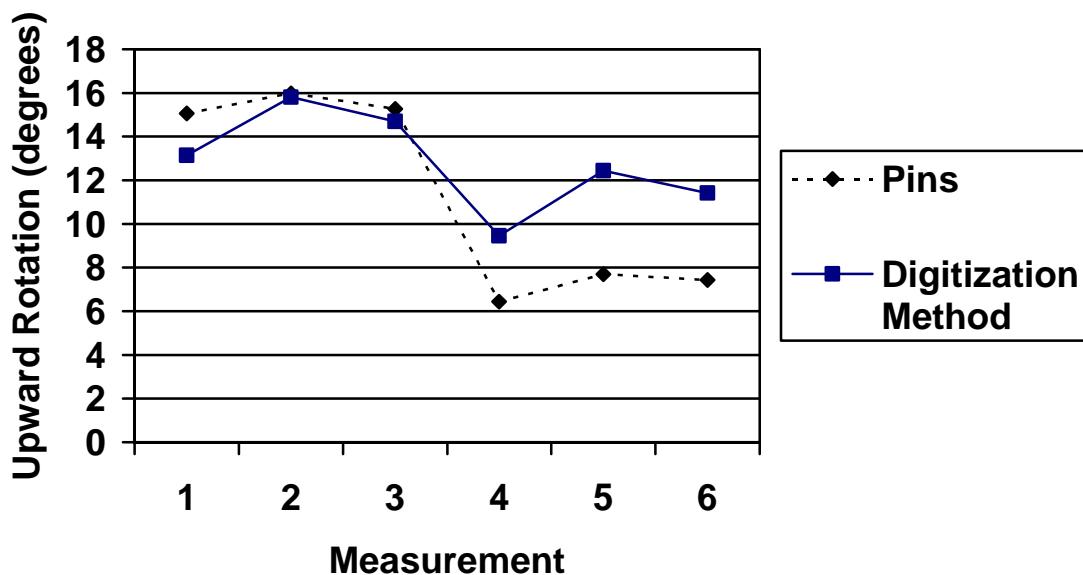
Patch	Tipping	Downward Rotation	Internal Rotation
1	1.3	1.6	1.8
2	1.1	1.7	1.5
3	4.1	2.6	1.3
4	3.1	1.2	0.7
5	2.5	1.7	1.0
6	1.4	1.1	1.0
7	2.0	0.9	1.6
8	2.3	1.5	1.0
9	2.5	1.6	1.2
10	2.3	1.5	1.0

### 2.3.3 Digitization Method

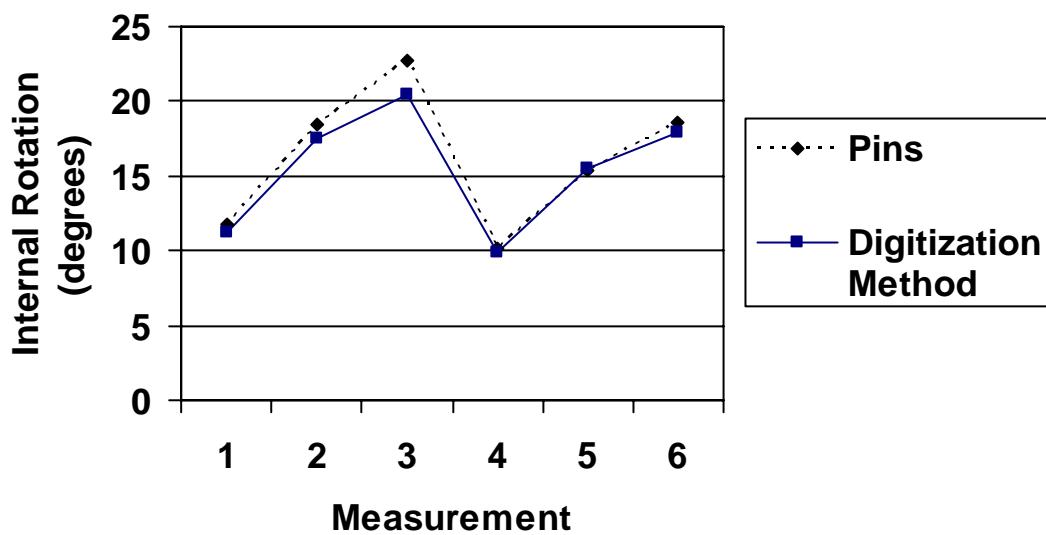
Digitization of bony landmarks is independent of skin motion so it was not affected by the bone pins. Errors ranged between  $-4.4^\circ$  and  $4.7^\circ$  (Table 2-3). The first three measurements were taken using method one while the last three measurements were taken using method two.

**Table 2-3** RMS error between pins and digitization method. Measurements 1 to 3 are method one (i.e. the optoelectronic markers). Measurements 4 to 6 are method 2 (i.e. the digitizer).

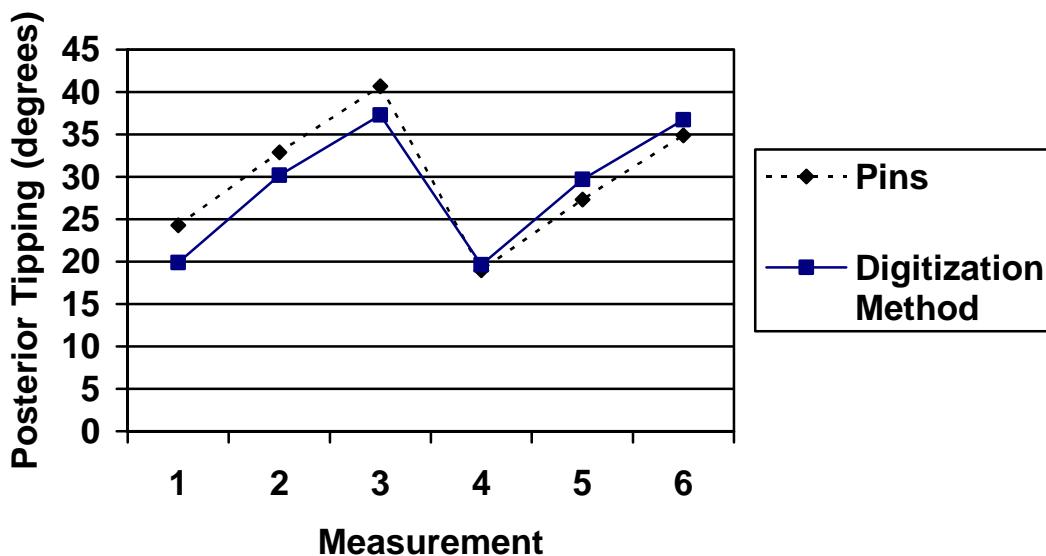
Measurement	Scapular tipping error	Upward rotation error	Internal rotation error
1	-0.6	-1.9	-4.4
2	-0.8	-0.2	-2.7
3	-2.2	-0.6	-3.4
4	-0.2	3.0	0.6
5	0.1	4.7	2.4
6	-0.7	4.0	1.8



**Figure 2-5** Comparison of pins and digitization method for upward rotation of the scapula. Measurements 1 to 3 are method one. Measurements 4 to 6 are method 2.



**Figure 2-6** Comparison of the pins and digitization method for internal rotation of the scapula. Measurements 1 to 3 are method one. Measurements 4 to 6 are method 2.



**Figure 2-7** Comparison of the pins and digitization method for posterior tipping of the scapula. Measurements 1 to 3 are method one. Measurements 4 to 6 are method 2.

## 2.4 Discussion

There were two main goals for this study. The first was to determine if bone pins could be used as a gold standard for validating our marker based measurement technique. Bone pins have been used as a gold standard for scapular motion but their effect on skin motion has not been assessed (Karduna *et al.*, 2001). The second was to determine the accuracy of measuring scapular movement by digitizing bony landmarks. This method has been used in the literature to assess scapular motion, but to date, its accuracy has not been published.

The major limitation in this study was the use of a cadaver instead of live subjects. This was a necessary step since it would be unethical to insert bone pins in a subject without knowing if the methods were valid. There are a number of differences between a cadaver and live subjects. The cadaver tissue was noticeably stiffer than live subjects and thus had less scapular motion. Movement in the cadaver was passive while future studies will involve active movement in healthy subjects. Active contraction of the muscles would make palpating bony landmarks more difficult. This may be accounted for by the stiff tissue in the cadaver.

An additional concern was the offset (difference in angles at the start of movement) between the patches with the pins in and the patches without the pins. There are two possible explanations. First, the act of inserting the bone pins changed the position of the patch markers relative to the scapula. Second, the act of inserting the bone pins moved the actual position of the scapula. The threaded bone pin did lift the skin and may have changed the position of the skin relative to the bone, but it was placed further away from the patch markers to minimize this problem. The act of drilling the pins into the lateral aspect of the acromion, removing them and then drilling them into the lateral scapular spine did move the

scapula. As reported, the difference between the pins and the patches decreased as the scapula reached the end of range. This is consistent with a different starting position (from the placement of the bone pins) and a similar end position as the scapula is guided into place by the movement of the arm and the presence of the rib cage underneath. Thus, pattern of the rms errors supports the theory that the actual starting position of the scapula changed.

Despite these limitations, the measured differences between the patches with the pins and without were small and were even smaller when the offset was removed. The use of bone pins appears to be valid for use as a gold standard in live subjects. An additional precaution will be taken to ensure the validity of our data in future studies. First, in the session in which the pins are inserted, each subject will perform each movement both with the pins in and without the pins. The pins can then be compared to the patches in the trial before the pins are inserted. In order to make sure the movements are performed reliably, extra time will be spent training the subjects and having them practice the movements.

Digitization of bony landmarks is one of the more common methods used in literature for measuring scapular motion, but to date has not been properly validated. Reliability has been published but not accuracy. Preliminary data from this experiment suggests that this method is accurate to within 5°. Further testing needs to be done in live subjects.

Very little difference was observed between the optoelectronic markers vs. the Optotrak probe in terms of accuracy. The Optotrak probe was much more convenient as the electrode tape on the optoelectronic markers kept losing its tackiness making it difficult to affix them to the scapula. Future studies will exclusively use the Optotrak probe for the digitization process.

## **2.5 Conclusion**

The lateral scapular spine appears to be the ideal position to place the bone pins since it is relatively easy to place at this point and there seems to be less skin movement. Threaded pins affect the position of the skin and should not be used. It appears that bone pins only have a minor effect on movement of the skin markers, and thus are a valid gold standard to use in live human studies. Data from this study is the first evidence that digitization of bony landmarks may be an accurate measure of scapular movement.

## **Chapter Three: Normal scapular movement**

### **3.1 Introduction**

Even though scapular movement is widely believed to be a factor in shoulder pathology (Borstad and Ludewig, 2002; Hebert *et al.*, 2002; Lukasiewicz *et al.*, 1999; Ludewig *et al.*, 1996; Ellen *et al.*, 2000; Mottram, 1997), very few studies have measured three-dimensional movement of the scapula either dynamically (McClure *et al.*, 2001; Koh T *et al.*, 1998; Lu TW *et al.*, 2002) or statically (Hogfors *et al.*, 1991) with a gold standard. Understanding how the scapula moves in a healthy population is essential to interpret how changes in this movement may affect shoulder pathology.

McClure et al (McClure *et al.*, 2001) looked at movement of the scapular during three different dynamic movements, scaption (humeral elevation in the scapular plane), flexion, and internal-external rotation with the arm flexed to 90° and elbow flexed to 90°. The movement of the scapula was measured with an electromagnetic marker attached to pins inserted into the scapula. They found that the scapula rotated upward, tilted posteriorly, and rotated externally with both flexion and scaption. There was less movement during internal-external rotation and it tended to occur at the end of the range of external rotation. The scapula upwardly rotated, tilted posterior and externally rotated.

Lu et al. (Lu TW *et al.*, 2002) used bone pins to measure scapular motion during wheelchair propulsion. They attached four reflective markers to the pins and used a 7-camera motion analysis system to track their movement. They did not publish their coordinate system nor did they state how they defined protraction or posterior tilting. They found that the scapula protracted, rotated downward and tilted posteriorly during the propulsion phase.

Koh et al. (Koh T *et al.*, 1998) also used reflective markers mounted on bone pins. They used helical axis parameters to characterize scapular motion. This makes it difficult to compare to other studies. They found that between 30° and 150° of humeral elevation, the scapula rotated about an axis perpendicular to the scapula. They also found that as the plane of elevation changed from more coronal to sagittal, the component of rotation parallel to the scapula (i.e. tipping) increased. This shows that there is more scapular tipping with abduction than with flexion.

Hogfors et al. (Hogfors *et al.*, 1991) used roentgen stereophotogrammetric analysis (RSA) to look at static positions of the scapula. Unfortunately, their non-standard coordinate systems made it very difficult to compare with other studies. The main conclusion from their study was that scapulohumeral rhythm was variable between subjects but relatively stable for any given subject.

There is a scarcity of data on dynamic scapular motion using gold standards in the literature. Of the three studies mentioned, one was a conference proceeding. Both of the two published studies concentrated on humeral elevation rather than functional movements. The objective of this study was to measure dynamic scapular motion during four different humeral movements, including two functional movements, and to measure the same day reliability of these movements.

## 3.2 Methods

### 3.2.1 Subjects

The inclusion criteria were that the subjects should be between 18-60 years of age and have normal skin integrity around the shoulder. Subjects were excluded if they were pregnant, had

osteoporosis, or had current shoulder pathology. Eight healthy subjects were recruited. Most were graduate students from the University of British Columbia. Subjects were given the choice of which shoulder they wanted to have tested. All chose their non-dominant left shoulder. Data from one subject was rejected due to pin loosening (see 3.3 Results). The average age of the remaining subjects was  $30\pm5$  years and they had BMIs ranging from 17- $30\text{kg}/\text{m}^2$ .

Ethics approval for the study was obtained from the Clinical Research Ethics Board at the University of British Columbia. All subjects gave informed consent before beginning the study.

### **3.2.2 Experimental Protocol**

The subject was seated on a stool with feet shoulder width apart and in firm contact with the ground. One optoelectronic marker carrier (with four infrared LEDs) was secured around the subject's waist and two marker carriers were secured to the subjects' upper arm. Marker carriers were secured by taping them to a strap placed around the humerus or trunk. Local anaesthetic was injected into the lateral scapular spine by an orthopaedic surgeon (W.R.). The subcutaneous tissue down to and including the periosteum was anaesthetized. Two non-threaded 1.6mm k-wires were then drilled into the lateral scapular spine by the surgeon and an optoelectronic marker carrier was secured to the exposed pins (Figure 3-1). With the subject's arms hanging by their side, the following points were digitized with the Optotrak probe: the spinous process of T<sub>7</sub>, the spinous process of C<sub>7</sub>, the sternal notch, the acromioclavicular joint, the root of the scapular spine, the posterolateral corner of the acromion and the inferior angle of the scapula. The three scapular points were digitized two

more times as well. The scapular points were digitized multiple times to obtain a more accurate measure of the starting position of the scapula.



**Figure 3-1** Bone pins with marker carrier. The other optoelectronic markers on the skin were from another study (Chapter 5). The picture on the right also shows humeral and trunk markers.

The four active movements tested in this study were glenohumeral abduction, forward reaching, glenohumeral horizontal adduction (H.Add), and hand behind back (HBB: glenohumeral extension, adduction, internal rotation). In forward reaching the subject reached forward to grab a pole. The pole was placed such that it was just inside the fingertips when the subject flexed their arm to 90°. These four movements put the scapula through nearly a full range of motion. The subjects were given several practice trials to ensure that they understood the proper movement pattern and timing. The subjects were instructed to take 3 seconds to perform the movement, 3 seconds to return to the resting position and 3 seconds to rest. Before each movement was recorded, the subjects held static

positions partway through the range of motion (2x at 1/3, 2x at 2/3, and 2x at full range of motion). The data from the recording of these static positions was used in later Chapters 4 and 5 of this thesis. After the static recordings for a particular movement, ten dynamic repetitions were recorded at 30Hz. using the optoelectronic camera system [Optotrak 3020, Northern Digital, Waterloo, ON]. After completion of the first dynamic trial of movement and all of the static recordings, an additional dynamic trial of each movement was recorded. The experiment was videotaped for documentation purposes.

### 3.2.3 Data Analysis

The local coordinate systems were as shown in Figure 2-3, except the X axis of the scapula was reversed in direction. This was done to maintain a right handed coordinate system since all subjects chose to have their left shoulder tested. In addition the Z axis of the humerus was taken as the midway point between the lateral and medial epicondyles to the acromioclavicular joint. The Euler angle sequence for the scapula with respect to thorax was external rotation ( $Z_S$ ), followed by upward rotation ( $Y_S$ ), followed by posterior tipping ( $X''_S$ ). Scapular motion has been shown to be sensitive to the Euler angle sequence chosen (Karduna *et al.*, 2000). This particular sequence was proposed by the International Shoulder Group of the International Society of Biomechanics (van der Helm, 2002). The Euler angle sequence for the humerus with respect to the thorax was ZYZ for humeral abduction, forward reaching, and horizontal adduction. The sequence was changed to ZXY for hand behind back because the ZYZ sequence ran into gimbal lock at  $0^\circ$  of humeral elevation. Angles were calculated as scapulothoracic and humerothoracic. Therefore, the angles at the start of

the movement were not zero but were the resting positions of the scapula and humerus with respect to the thorax.

For each movement, the rotation angle sequences were split into forward and reverse phases. They were then normalized to humeral motion and percentage of movement. For abduction and forward reaching it was normalized to humeral elevation. For hand behind back it was normalized to humeral internal rotation and for horizontal adduction it was normalized to angle of humeral elevation. The ten repetitions were then averaged together.

### 3.2.3.1 Reliability

Same day reliability of scapular movement was tested between trials one and two with intraclass correlation coefficients ICC(3,10) and an rms difference.

The ICC was calculated for each of the four movements. For abduction, reaching, and H.Add, the ICC was calculated using the data normalized to humeral motion, while for HBB the ICC was calculated using the data normalized to percentage movement. This was because the HBB movement was not well suited to normalization to humeral motion. Therefore, ICC(3,10) was calculated for each angle of humeral motion for abduction, reaching and H.Add, and for each percentage of movement for HBB.

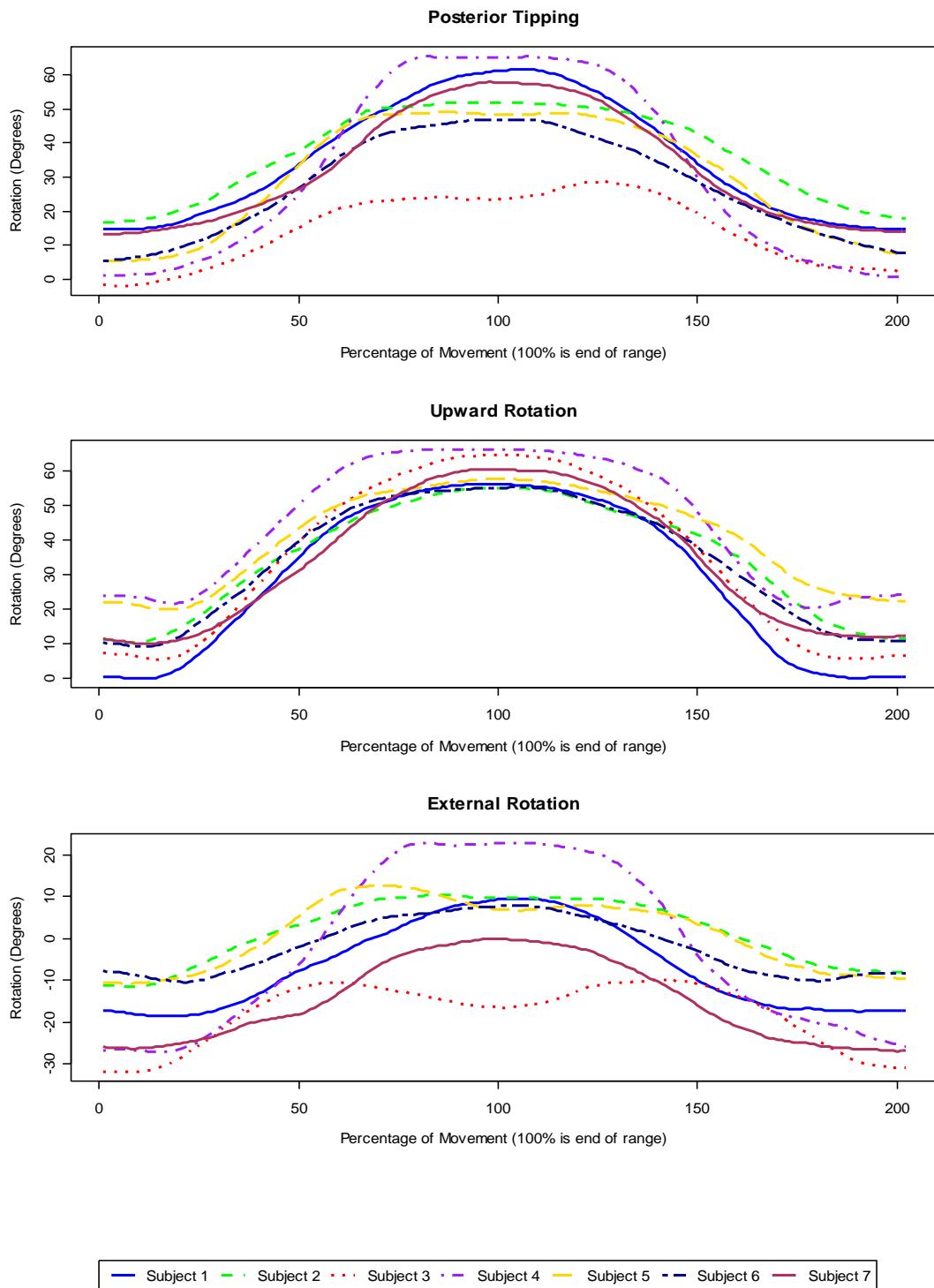
The rms difference between trial one and trial two was calculated for each of the four movements and for each angle as an aggregate across all subjects. It was also calculated individually for each subject. As with the ICC calculation, the data normalized to humeral motion was used for abduction, reaching, and H.Add, while the data normalized to percentage of movement was used for HBB.

### 3.3 Results

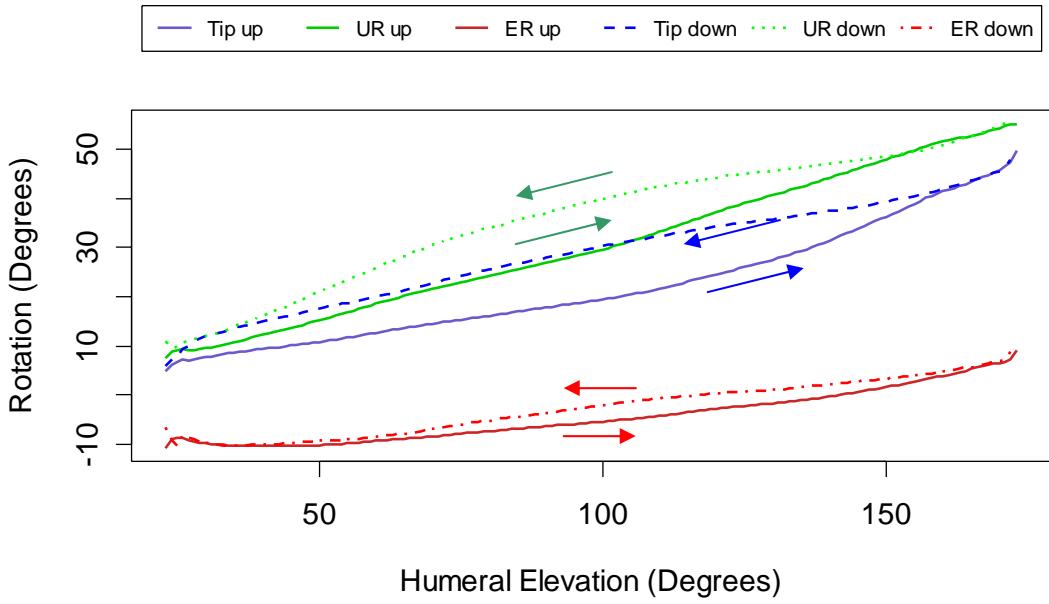
The data for one subject was rejected. When removing the pins the surgeon noted that the pins were loose. Data and video footage of the experiment were reviewed, but could not identify a point in time when the pins failed. There appeared to be differences in the resulting movement patterns from those observed in other subjects. Although these differences could be due to individual variation, it was felt that it would be better to reject the data since we could not be confident in our gold standard.

Abduction was a consistent movement for the remaining seven subjects. The scapula tipped posteriorly ( $44\pm11^\circ$ ), upwardly rotated ( $49\pm7^\circ$ ) and externally rotated ( $27\pm11^\circ$ ) during the movement (Figure 3-1). At the start of the movement there was consistently a small amount (couple of degrees) of downward rotation. Most subjects achieved greater than  $50^\circ$  posterior tipping except for subject 3 who achieved less than  $30^\circ$ .

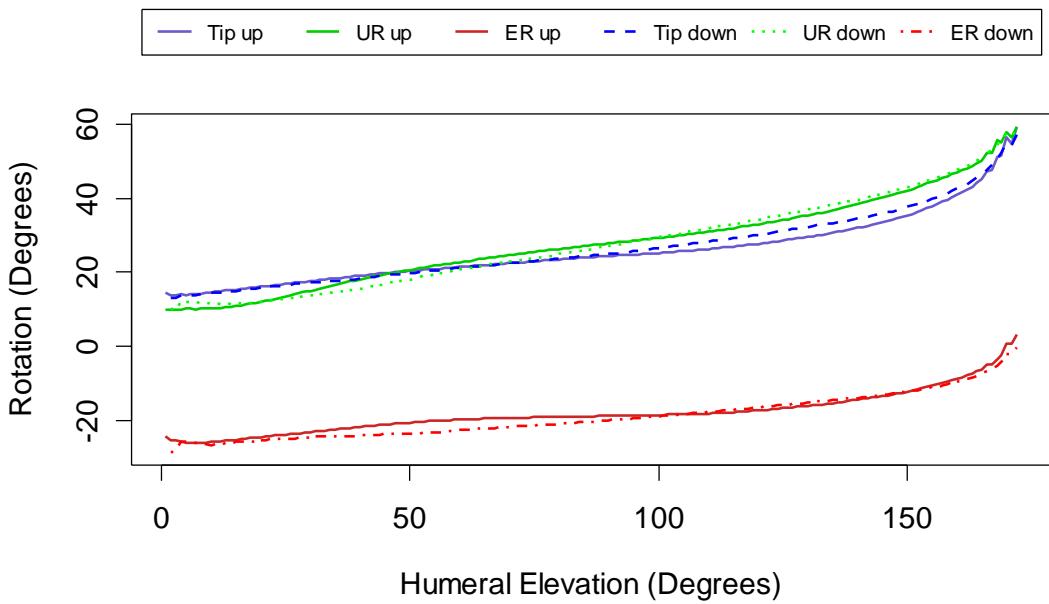
An interesting feature of the abduction movement was the difference between the concentric and eccentric phases. This was also present in the other movements but was not as pronounced. There was a marked difference in some subjects (Figure 3-3) while almost no difference in others (Figure 3-4). The area between the concentric and eccentric phases is shown in Table 3-1.



**Figure 3-2** Abduction: Posterior tipping, upward rotation and external rotation for all seven subjects.



**Figure 3-3** Abduction (subject 6) Large difference between concentric and eccentric movement. The arrows point in the direction of movement.



**Figure 3-4** Abduction (subject 7) Small difference between concentric and eccentric movement.

**Table 3-1** Area of hysteresis between eccentric and concentric phases of abduction. Units in degrees squared. A negative number infers that the eccentric phase has generally greater scapular angles than the concentric phase.

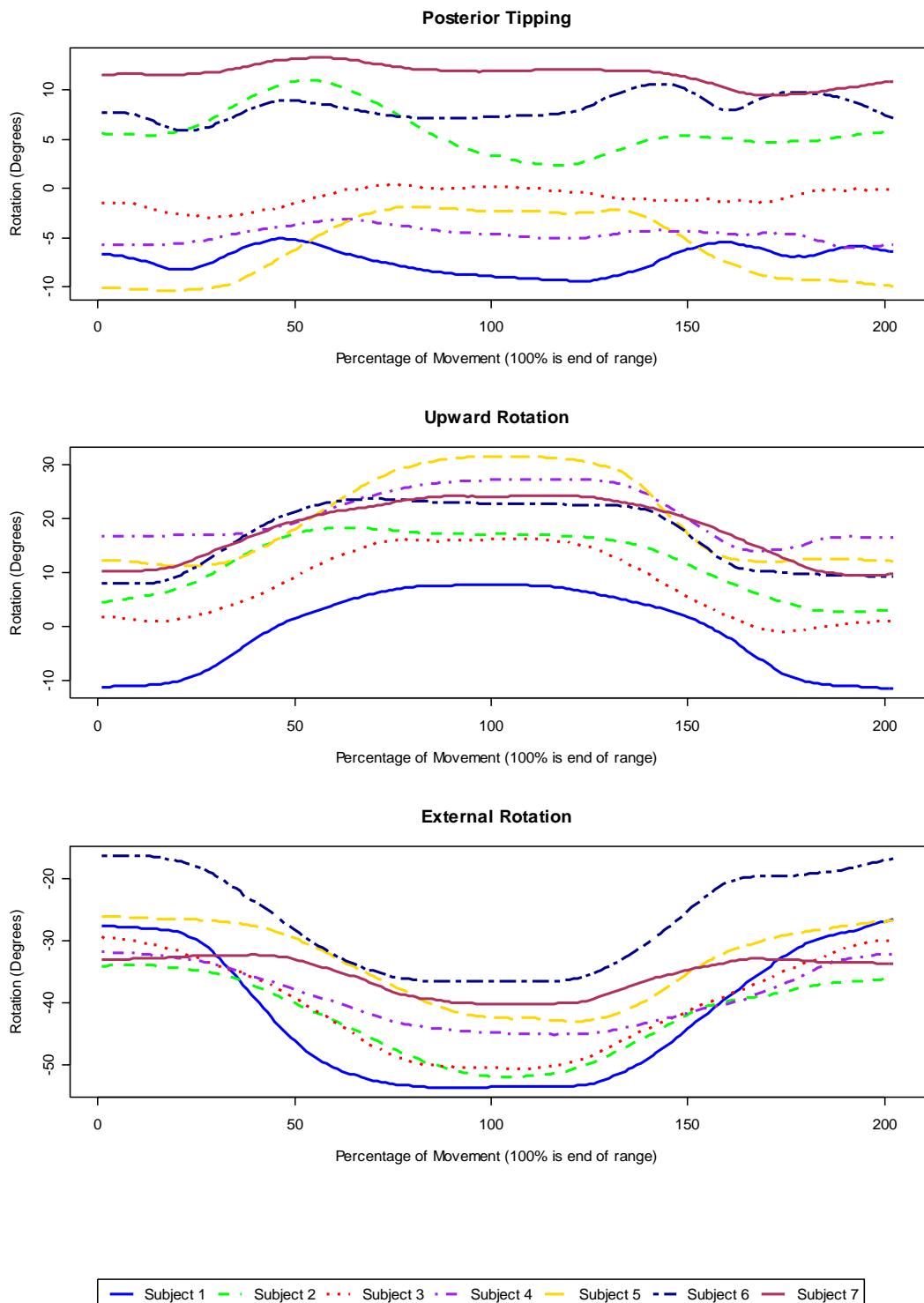
	<b>Posterior Tipping</b>	<b>Upward Rotation</b>	<b>External Rotation</b>
Subject 1	-537	-303	-153
Subject 2	-579	-535	-133
Subject 3	-879	-508	-461
Subject 4	-1088	-190	-854
Subject 5	-683	-640	104
Subject 6	-1008	-838	-268
Subject 7	-129	33	173

For reaching the scapula consistently upwardly rotated ( $17\pm3^\circ$ ) and internally rotated ( $18\pm6^\circ$ ). Tipping was variable ( $5\pm2^\circ$ ) although generally less than  $10^\circ$  (Figure 3-5). In some subjects the pattern was asymmetric while in others it was more symmetric. Both patterns are more complex than for upward rotation or external rotation as there were multiple changes in direction of rotation.

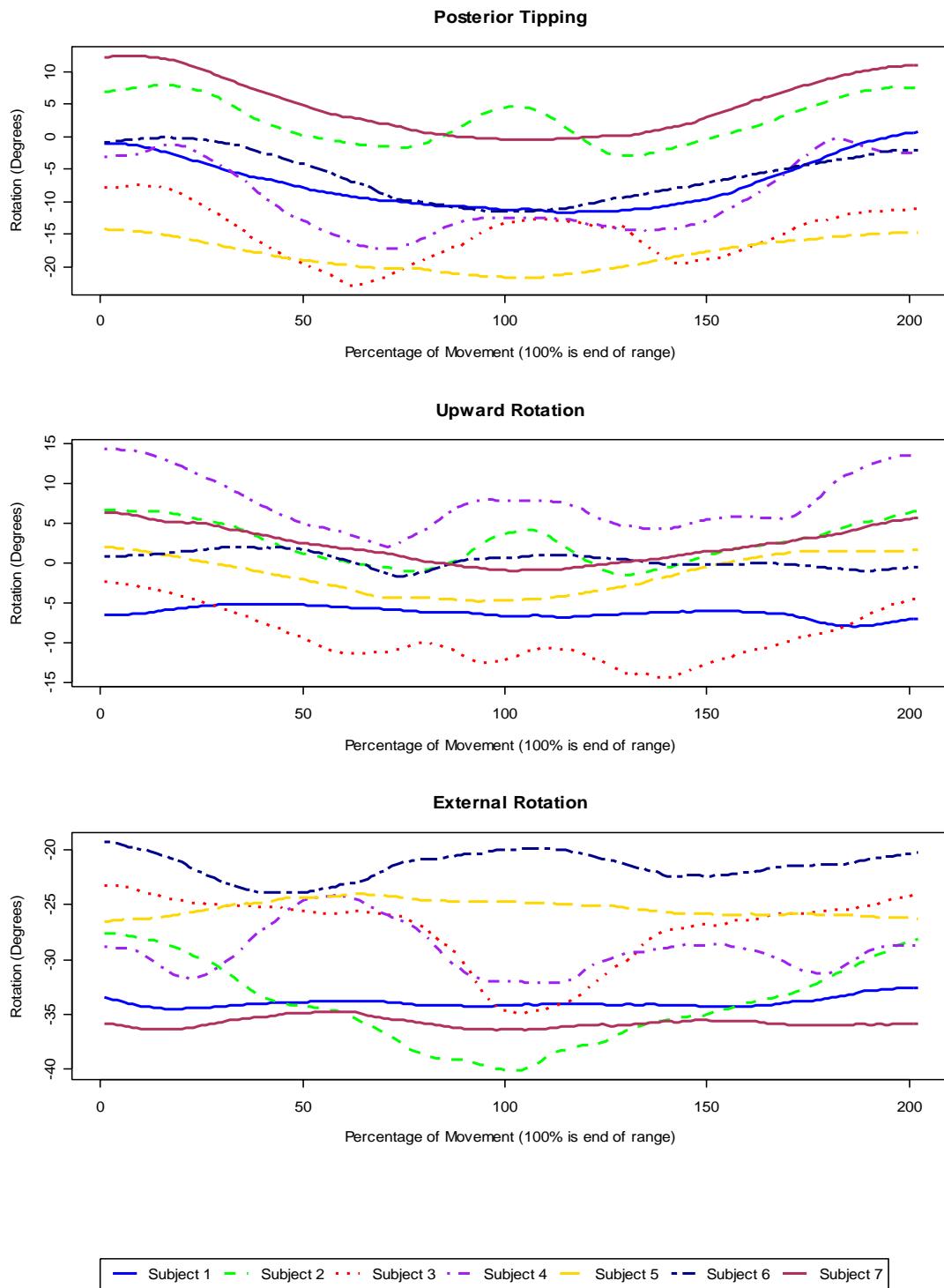
During the hand behind back movement two subjects experienced some discomfort (subjects 1 and 3). Overall the range of scapular movement with this motion was small (Figure 3-6). Most rotations did not exceed  $15^\circ$ . The movement was quite variable amongst the different subjects. Subjects tended to use a variable combination of anterior tipping ( $13\pm3^\circ$ ) and downward rotation ( $8\pm4^\circ$ ) to complete the movement. The amount of external rotation

( $6\pm5^\circ$ ) was quite variable. Three of the seven subjects had a double peak of anterior tipping. The first was just after the midway mark during the movement and the second just before the midway mark on return. All but one subject's scapula rotated downward, the exception rotated upward a couple of degrees. Two showed a clear double peak as with anterior tipping and two subjects had an irregular pattern (anterior tipping with some irregularities). External rotation ranged from a few degrees of external rotation to  $15^\circ$  of internal rotation. One subject showed an interesting pattern where the scapula internally rotated for the first 25% of movement, externally rotated to  $5^\circ$  by the 60% mark, and then internally rotating until the end of range. The return motion showed a similar pattern but without as much external rotation.

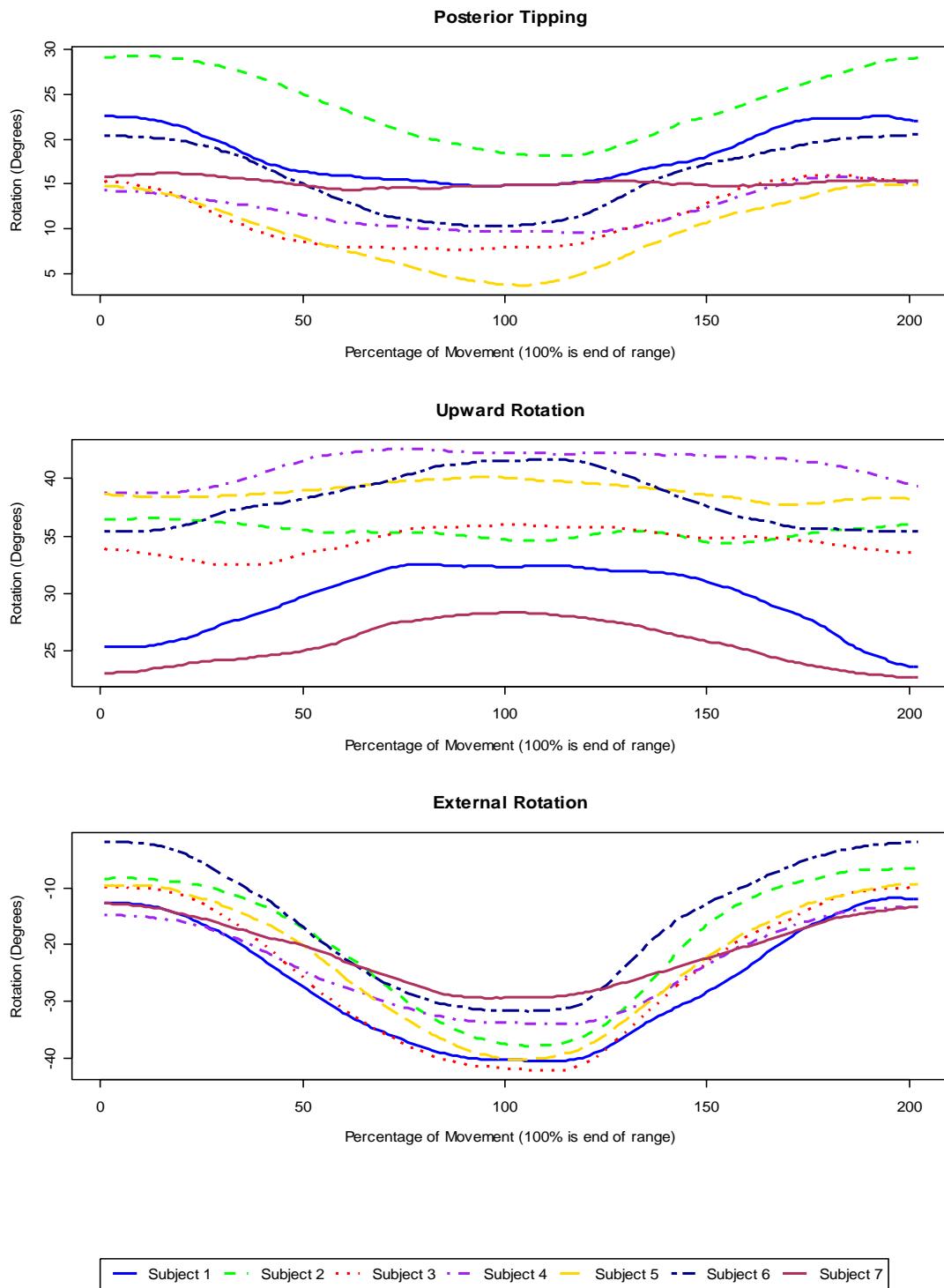
For H.Add there were small amounts of anterior tipping ( $8\pm3^\circ$ ). Upward rotation ( $5\pm2^\circ$ ) varied from nothing to a few degrees of upward rotation. The most prevalent rotation during this movement was internal rotation ( $27\pm6^\circ$ ) (Figure 3-7).



**Figure 3-5 Reaching:** Posterior tipping, upward rotation and external rotation for all seven subjects.



**Figure 3-6** Hand Behind Back: Posterior tipping, upward rotation and external rotation for all seven subjects.



**Figure 3-7** Horizontal Adduction: Posterior tipping, upward rotation and external rotation for all seven subjects.

### 3.3.1 Reliability

The rms differences between trial one and trial two ranged from  $1.1^\circ$  to  $4.7^\circ$  (Table 3-2).

**Table 3-2** RMS differences between trial one and trial two for the three different rotations.

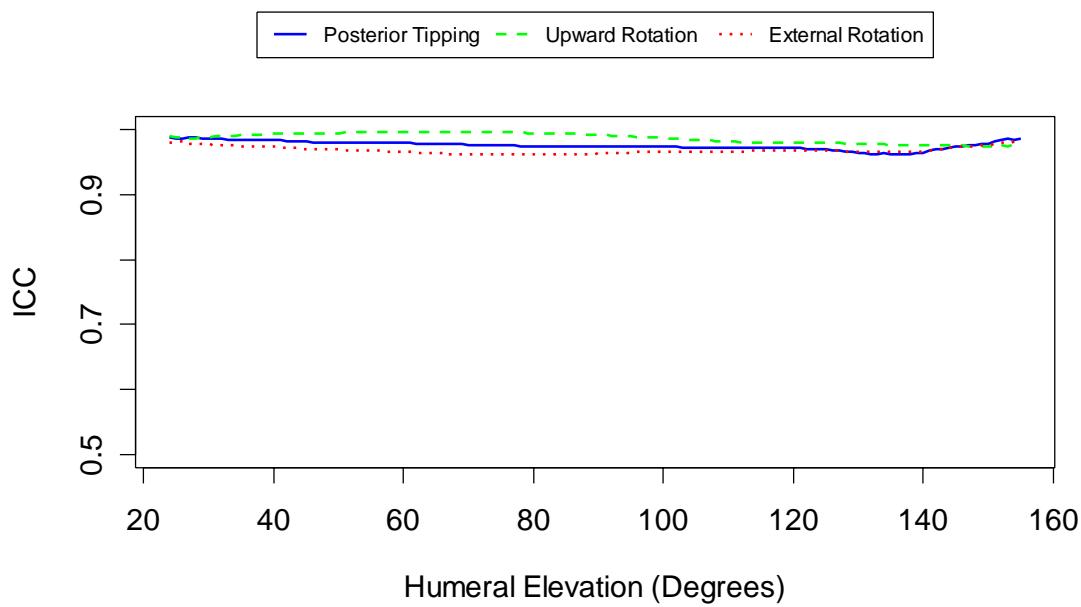
	Posterior tipping	Upward rotation	External rotation
Abduction	1.9	1.2	2.0
Reaching	4.0	2.8	3.9
Hand Behind Back	2.0	4.7	3.3
Horizontal Adduction	1.7	1.1	2.1

The abduction movement was very reliable with the ICC(3,10) staying above 0.96 throughout range (Figure 3-8).

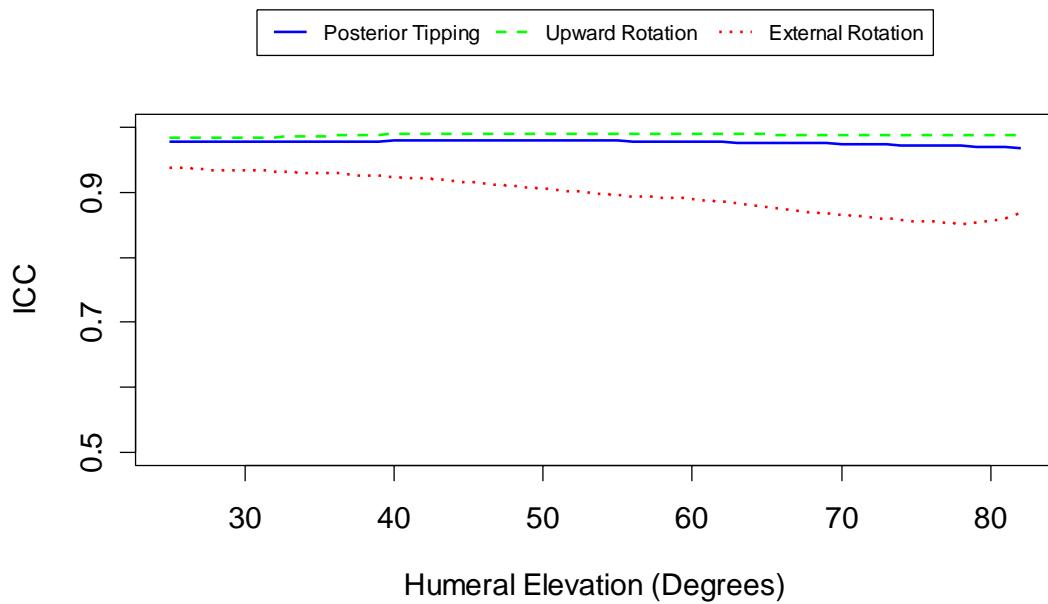
For reaching, posterior tipping and upward rotation were very reliable with ICC(3,10) staying above 0.97 through range while external rotation started at 0.94 and decreased to approximately 0.85 at the end of range (Figure 3-9).

The hand behind back movement was not as reliable. The ICCs for posterior tipping stayed above 0.9, but the ICCs for upward rotation decreased to 0.5 near the end of range and the ICCs for external rotation ranged between approximately 0.7-0.95 (Figure 3-10).

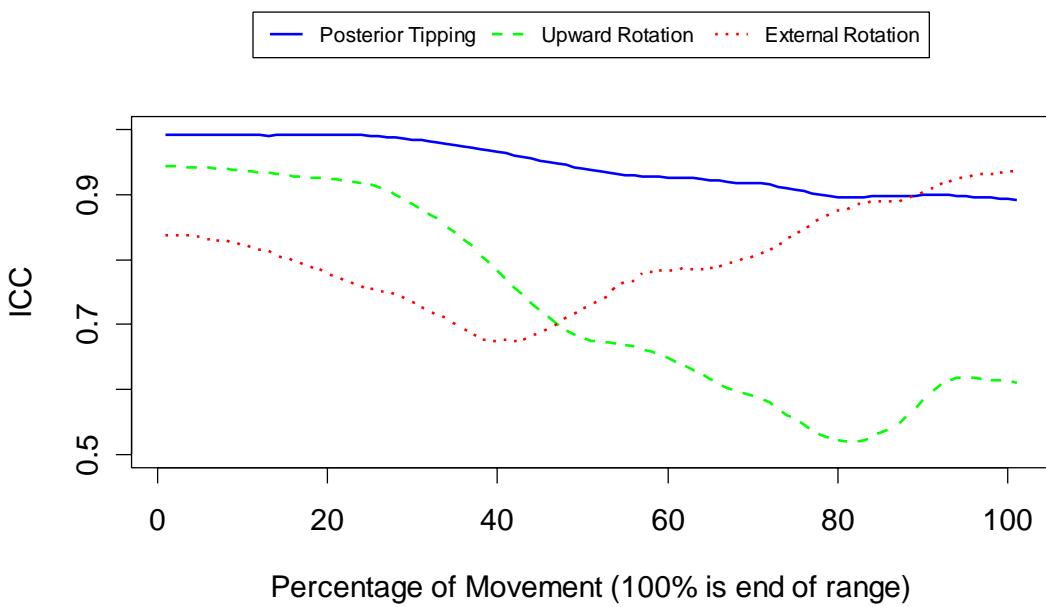
Horizontal adduction was more reliable. The ICCs for upward rotation stayed above 0.98 while the ICCs for posterior tipping and external rotation stayed above 0.93 (Figure 3-11).



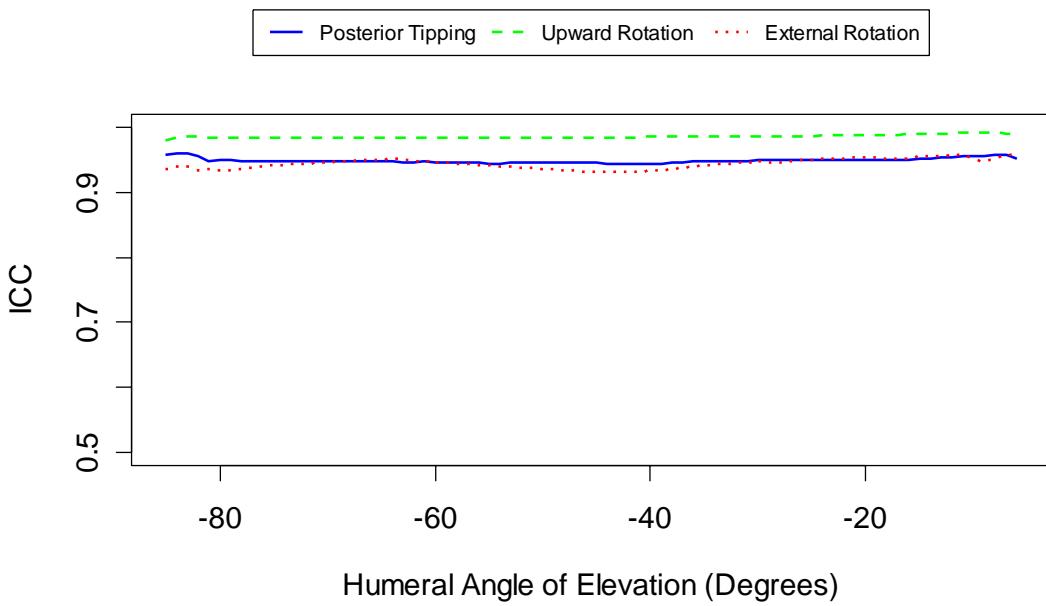
**Figure 3-8** Abduction:  $\text{ICC}(3,10)$  through range of humeral elevation.



**Figure 3-9** Reaching:  $\text{ICC}(3,10)$  through range of humeral elevation.



**Figure 3-10** Hand Behind Back: ICC(3,10) through movement.



**Figure 3-11** Horizontal Adduction: ICC(3,10) through humeral rotation.

### **3.4 Discussion**

This study described motion for four different arm movements. During abduction, the scapula tipped posteriorly, upwardly rotated, and externally rotated. During reaching, the scapula upwardly rotated and internally rotated with a variable but small amount of scapular tipping. HBB was a small and variable movement usually consisting of anterior tipping, downward rotation and a variable amount of internal rotation. For H.Add, internal rotation was the predominant rotation but there were also small amounts of anterior tipping and upward rotation. Abduction and H.Add were the most reliable. External rotation was almost as reliable except for external rotation (ICC dropped to 0.85). HBB was the least reliable movement with ICCs as low as 0.5.

One of the limitations of this study was the use of a lumbar marker carrier instead of thoracic. It was felt that placing the marker carrier over the thoracic spine would not be appropriate because of possible skin movement during the various arm movements. The sternum has been used in other studies but was unavailable for this study because the single camera for this study needed to be posterior to the subject to view the scapular markers and to digitize the posterior landmarks. Subjects were instructed to sit up straight during the testing and little trunk movement was observed. Therefore, it was unlikely that the placement of the markers had a significant effect on the measured angles. It has been suggested that there is movement in the thoracic spine during humeral elevation (Theodoridis and Ruston, 2002; Willems *et al.*, 1996) therefore, even markers on the sternum may be an approximation. Sample size in this study was limited to seven subjects. This is an inherent problem in studies using invasive measures. Despite this limitation, this study showed a large range of

scapular movement in some directions and remarkable consistency in other directions. The addition of more subjects would always be beneficial.

Another possible limitation was that the use of bone pins would alter normal movement.

Only two subjects reported any pain with movement and that was only with the hand behind back movement. The movement patterns of both of these subjects were not obviously different from the other subjects.

As mentioned by McClure et al.(McClure *et al.*, 2001) there are very few studies which measure scapular motion dynamically with a gold standard. Differences between the studies in axis systems, angles sequences and types of angles (i.e. helical, cardan, projection) make it hard to compare. The main difference between this study and McClure et al.'s was the definition of the scapular x axis. They used the line connecting the medial root of the scapular spine to the acromioclavicular joint while this study used the line connecting the medial root of the scapular spine to the posterolateral acromion. These landmarks were chosen based on the recommendations of the International Shoulder Group of the International Society of Biomechanics (ISB) (van der Helm, 2002). This coordinate system has the advantage that the posterolateral acromion is thought to result in fewer problems with gimbal lock (de Groot, 1997). Due to the ISB recommendations, we decided to adopt their proposed standard.

To check the effect of using a different coordinate system, the data from two subjects were recalculated using the same reference system as McClure et al. The general movement patterns were very similar. In their study the resting position of the scapula was in more internal rotation. During abduction, upward rotation and external rotation were greater than

this study. This may be why McClure et al. reported achieving greater external rotation than previous studies (van der Helm and Pronk, 1995; McClure *et al.*, 2001; Ludewig *et al.*, 1996; Meskers *et al.*, 1998).

The choice of movements for this study was designed to test a wide range of scapular motion and to test slightly different movements than McClure et. al. (McClure *et al.*, 2001).

Comparing the results of this study for abduction to McClure et al's results for scaption and flexion show some remarkable similarities. For all three movements the scapula tilted posteriorly, upwardly rotated and externally rotated. For scapular plane abduction they found that the scapula posteriorly tipped  $30\pm13^\circ$ , upwardly rotated  $50\pm4.8^\circ$ , and externally rotated  $24\pm12.8^\circ$ . This was very similar to our results for coronal plane abduction where the scapula posteriorly tipped  $44\pm11^\circ$ , upwardly rotated  $49\pm7^\circ$  and externally rotated  $27\pm11^\circ$ . The difference in posterior tipping may be because it was a slightly different movement or due to differences in the coordinate systems.

This study also showed that there was often a difference between the concentric and eccentric phase of the movement as did McClure et al. (McClure *et al.*, 2001). This contrasts with de Groot et al. (de Groot *et al.*, 1998) who found that the difference was "negligibly small." de Groot et al. used two-dimensional x-rays to measure scapular motion which may explain some of the differences. The differences between concentric and eccentric phases which we recorded showed a large variability. Anecdotally, it was interesting to note that one of the subjects with the largest differences reported that he previously had problems with that shoulder. The subject with the least amount of difference was previously a ballet dancer and reported that her instructors spent a lot of time training her shoulder movement. It is impossible to make conclusions from two subjects but this does coincide with the author's

clinical experience that patients with shoulder problems qualitatively have different concentric and eccentric phases. There is some evidence in the literature supporting this (Borstad and Ludewig, 2002).

The reaching movement tested was very similar to sagittal plane flexion, the main differences being the degree of humeral elevation and the addition of a protraction component. McClure et al.(McClure *et al.*, 2001) tested pure sagittal flexion with bone pins. They found that the scapula externally rotated during this movement. This finding contrasts with this study which found internal rotation.

These differences and similarities build a good picture of what guides scapular movement. It appears that the relationship between the scapula and the ribcage is key to determine whether the scapula externally or internally rotates. With pure flexion, the clavicle is free to move posteriorly. If the medial border of the scapula is kept against the ribcage from activity of the serratus anterior, the net effect will be scapular external rotation. If on the other hand the clavicle moves anteriorly during a reaching movement, the medial border of the scapula will be kept relatively posterior as the rib cage holds it back. This will bring the scapula into more internal rotation. This internal rotation may be very important clinically as it has been shown that protraction decreases the subacromial space (Solem-Bertoft *et al.*, 1993).

The hand behind back movement was quite variable amongst all the subjects. Subjects tended to use a combination of downward rotation, internal rotation and anterior tipping to bring the hand behind the back. The overall range of motion was low with most movements below 15°. This suggests that most of the movement is occurring at the glenohumeral joint rather than the scapula. This has the potential to increase the strain in the glenohumeral joint,

possibly stretching the posterior capsule or impinging the anterior capsule or biceps tendon. It is not surprising that this movement is often restricted clinically. The double peak in some subjects may be because bringing the hand around to the back of the body needs more scapular range than moving the hand further up the back.

Not only were the more functional movements of reaching and hand behind back more variable between subjects, but they were also more variable within subjects. The rms difference between trials was higher and the ICCs were lower for these movements. For abduction and H.Add the rms differences ranged from 1.1- 2.1° while for reaching and HBB they ranged from 2.0- 4.7° for the different angles. The ICCs for abduction and H.Add stayed consistently high. For reaching, the ICCs decreased near the end of range. This may be partly due to difference in the placement of the pole which the subjects reached for. For HBB the ICCs were considerably lower throughout most of the range suggesting that subjects are not using a consistent pattern.

This brings up an interesting dilemma. Reliability is needed to detect differences between subject populations (i.e. subjects with shoulder pathology and subjects with normal shoulders). On the other hand, if we do not test functional movements the differences may be meaningless since they do not correspond to real life situations.

## **Chapter Four: Accuracy of Digitization of Bony Landmarks**

### **4.1 Introduction**

One way to overcome the problem of the scapula sliding under the skin is to track bony landmarks instead of skin markers. This can be done non-invasively by palpating the landmarks and then using a device to digitize their locations. This has been a popular method in the literature. It has been used to measure the effects of external loads (Pascoal *et al.*, 2000; de Groot *et al.*, 1999), the effects of 2-D roentgen projection (de Groot, 1999), to compare muscle activity with movement (Ludewig *et al.*, 1996) and to compare the scapular orientation in subjects with and without shoulder pathology (Hebert *et al.*, 2002; Lukasiewicz *et al.*, 1999).

Various different methods have been used to palpate and digitize the landmarks. Some studies used mechanical linkage systems while others used electromagnetic or optoelectronic systems. Sometimes each point was digitized separately. Other studies used special jigs which located all the points at once.

Van der Helm and Pronk (van der Helm and Pronk, 1995) used a mechanical linkage system to digitize the locations of the acromioclavicular joint, the inferior angle of the scapula, the posterolateral acromion, and the trigonum spinae. As a measure of accuracy they calculated standard deviation of the distance between each pair of landmarks. They found the standard deviations were between 1.5 and 5.2mm and 2°. This is an indirect method of determining accuracy by determining how closely the measured points represent a rigid body, and it certainly isn't the same as measuring accuracy against a gold standard.

Meskers (Meskers *et al.*, 1998) further developed this method to measure the posterolateral acromion, inferior angle of the scapula and trigonum spinae with a special locator attached to an electromagnetic sensor. They found that they could take approximately one measurement per second with this device. Inter-trial variability ranged from 2.0-2.5° and inter-day variability ranged between 3.0°-4.2°.

Barnett et al. (Barnett *et al.*, 1999) used a special locator with three legs which was designed to reliably locate the three landmarks. This locator was connected to an IsotrakII™ system to measure the locator's position. Two sets of experiments were done. In the first, arm motion was measured using a fluid-filled goniometer. In the second, arm motion was measured using real time feedback from a sensor mounted on the arm. In both experiments, the subjects performed arm abduction (coronal plane) from 0° to 90° in 10° increments. At each interval the locator was applied. They found the 95% confidence level to be 4° of rotation and 10mm of translation. The angles they measured ranged from 0°-30° of upward rotation, 0°-5° of posterior tipping and 0°-5° of external rotation. The confidence interval did not seem to change much for the different positions throughout range. These results are very promising but there are two significant limitations with this study. The first was that only one movement was tested. Reliability may be different for other movements. The second was that the movement was stopped at 90°. This is approximately half of the normal shoulder's normal range of abduction.

Hebert et al. (Hebert *et al.*, 2000) conducted a similar study using an optoelectronic probe to monitor the bony landmarks. They included both flexion and abduction but stopped at 110° for both. They found the coefficient of variation to be less than 10% for most movements.

To assess concurrent validity of this method, they mounted optoelectronic markers on a

model of the scapula. They then placed the scapula model in different positions and measured its position with the probes and the attached markers. This is not a very convincing method to assess concurrent validity because the bony landmarks are visible and there is no soft tissue between the probe and the bone. As in Barnett et al (Barnett *et al.*, 1999), the number of movements and ranges of motion tested were very limited, and it was also a static measure.

These studies suggest that there is considerable interest in the digitization method for measuring scapular motion. The reliability of this method has been addressed although not for a range of shoulder movements. Despite attempts at documenting accuracy, it is clear that no one has yet compared the digitization method to a gold standard. Therefore, the objective of this study was to determine the accuracy of the digitization of bony landmarks by comparing it to bone pins. It was hypothesized that the digitization of bony landmarks would have a root mean squared (rms) accuracy of less than 5° for each rotation and that the accuracy of this method would vary, depending on the position of the arm.

## **4.2 Methods**

### **4.2.1 Subjects**

The subjects for this study were the same as described in Chapter 3 on pages 24-25. For brevity, this description is not repeated here.

### **4.2.2 Experimental Protocol**

The subjects were set up as in Chapter 3. The same four movements (abduction, reaching, hand behind back, horizontal adduction) were tested except that for each movement three

static positions were held twice. The first position was at approximately 1/3 of maximum range of motion, the second at 2/3 of maximum range of motion and the last at maximum range of motion. Horizontal adduction (H.Add.) was different because the neutral position was not the start position. For H.Add, the first position was at the starting position, the second at the halfway mark and the third at the end of movement. For hand behind the back the 2/3 position would often obstruct the thoracic markers and was adjusted to make sure they were visible.

As each position was held, each landmark was localized by palpation and the Optotrak probe was placed at the proper location. The locations of the tip of the digitizing probe with respect to the probe LEDs was known, so the location of each digitized point in the camera's coordinate system could be calculated. For each digitized point a two to three second recording of all marker locations was taken using the optoelectronic camera [Optotrak 3020, Northern Digital, Waterloo, ON].



**Figure 4-1** Digitization of the medial root of scapular spine with the Optotrak probe. Also visible are the bone pins and attached marker carrier. The other visible markers were part of another study.

### **4.2.3 Data Analysis**

Kinematic data was analyzed as described in Chapter 3. Digitized points were used to calculate a transformation matrix (and resulting Euler angles) between the location of the digitization points in the neutral position and each of the other recorded positions.

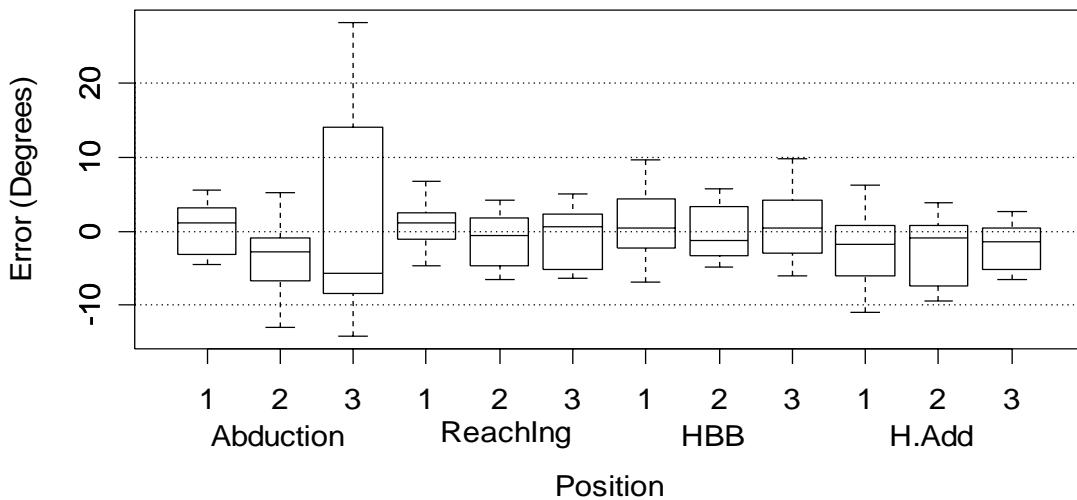
To determine the accuracy of the digitization of bony landmarks, mean absolute and root mean square (rms) errors were calculated between the pins and the digitization method. A one way repeated measures ANOVA was used to determine if the mean or rms error depended on the position measured. If the Huynh Feldt epsilon was less than 0.7, it was deemed that the sphericity assumption was violated and an adjusted p value was then used. Posthoc testing was performed using Tukey's HSD. A p value of 0.05 was accepted as significant.

## **4.3 Results**

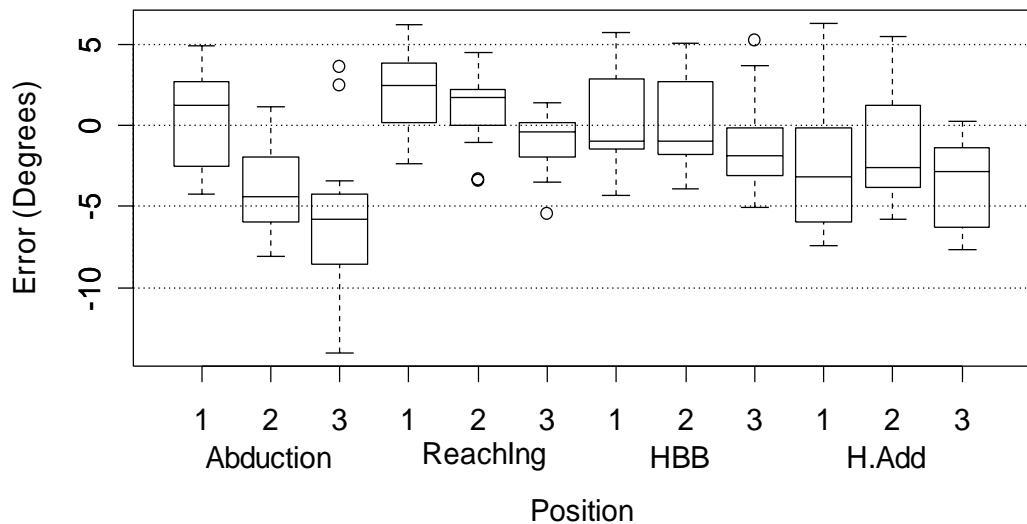
The mean absolute errors were  $-0.8^\circ$  for scapular tipping,  $-1.3^\circ$  for upward rotation, and  $0.9^\circ$  for external rotation. Figures 4-2 to 4-4 show the distribution of the errors for each of the different positions digitized, while Tables 4-1 to 4-4 show the mean absolute and rms errors for each position.

None of the differences in mean errors for posterior tipping in each position were significant ( $p=.42$ ). The differences between the mean absolute errors in external rotation ( $p=0.07$ ) were marginally significant. The differences in mean absolute errors for upward rotation were significant ( $p<0.0001$ ). The results of Tukey's HSD showed that position 1 of abduction (mean=  $0.3^\circ$ ) was significantly higher than position 2 of abduction (mean=  $-4.0^\circ$ ), position 3 of abduction (mean=  $-5.8^\circ$ ) and position 3 of H.Add (mean=  $-3.6^\circ$ ). Position 2 of abduction was

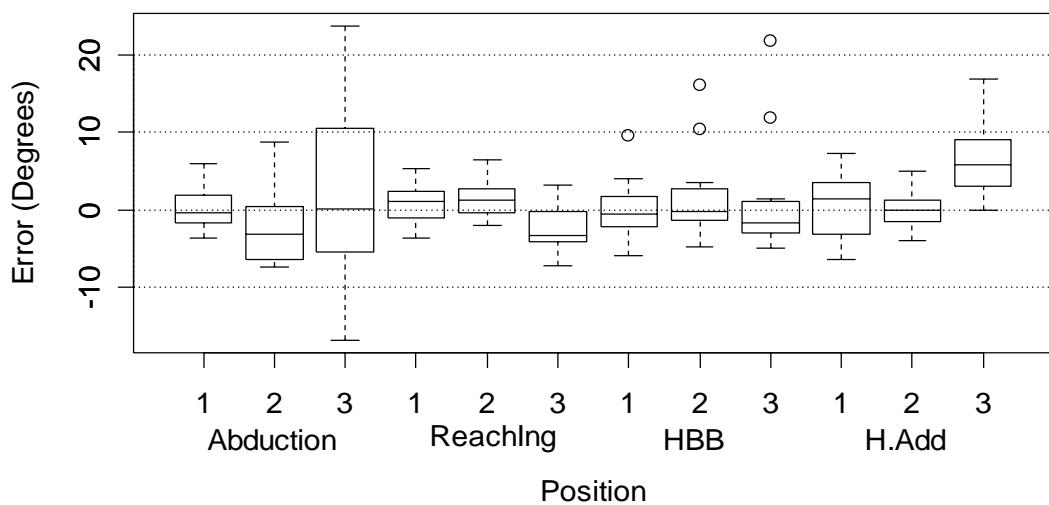
significantly higher than positions 1 (mean=2.0°) and 2 (mean=0.9°) of reaching as well as position one of HBB (mean=0.1°). The mean absolute error of position 3 of abduction was significantly less than every other position except for positions 2 of reaching and positions one (mean=-2.5°) and two of H.Add (mean=-3.6°). Position 1 of reaching was also different from positions 1 and 3 of H.Add while position 3 of reaching (mean=-0.9) was significantly different from position 3 of H.Add but not position 1.



**Figure 4-2** Posterior tipping: Boxplot showing absolute error distribution for all 12 positions. Midline of the box is the median value. The outer edges of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentiles. The outer whiskers indicate the outer range up to 1.5 times the interquartile range. Any data outside the whiskers are outliers.

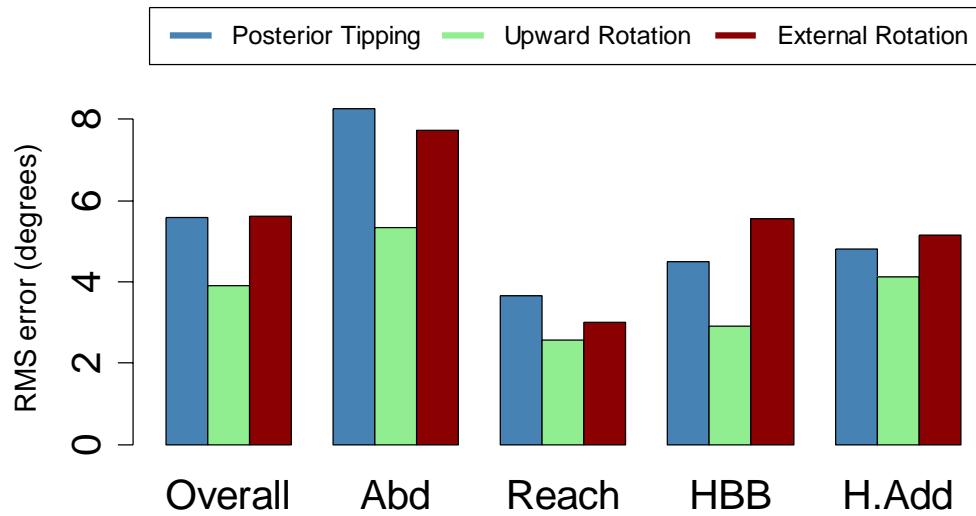


**Figure 4-3** Upward Rotation: Boxplot showing the absolute error distribution for all 12 positions.



**Figure 4-4** External Rotation: Boxplot showing the absolute error distribution for all 12 positions

The overall rms errors ranged from  $3.9^\circ$  to  $5.6^\circ$  while the rms errors for individual movements ranged from  $2.6^\circ$  to  $8.2^\circ$  (Figure 4-5). The full abduction position (position 3) had considerably higher rms errors than the other positions (posterior tipping:  $12.5^\circ$ , upward rotation:  $7.3^\circ$ , internal rotation:  $12.0^\circ$ ). An analysis of the different positions found significant differences in the rms errors for all three rotations (posterior tipping  $p<0.006$ , upward rotation  $p<0.0001$ , external rotation  $p<0.003$ ). Position 3 of abduction had significantly greater errors than every other position for every rotation with the following exceptions: for upward rotation it was not significantly different than position 2 of abduction or position 1 of H.Add and for external rotation it was not different from position 3 of H.Add, nor position 3 of HBB. Position 3 of reaching had significantly smaller errors than position 2 of abduction. If position 3 of abduction was removed from the analysis overall rms errors dropped to  $4.5^\circ$  for posterior tipping,  $3.5^\circ$  for upward rotation, and  $4.6^\circ$  for internal rotation.



**Figure 4-5** RMS error for digitization process for each movement and Euler angle.

**Table 4-1** Abduction: rms and mean absolute error for the three different positions of abduction.

	Posterior tipping		Upward rotation		Internal rotation	
	RMS error	Mean error	RMS error	Mean error	RMS error	Mean error
Position 1	3.5	0.3	3.0	0.3	2.7	0.4
Position 2	6.0	-3.8	4.9	-4	5.3	-1.8
Position 3	12.5	0.3	7.3	-5.8	12.0	3.4

**Table 4-2** Reaching: rms and mean absolute error for the three different positions of reaching.

	Posterior tipping		Upward rotation		Internal rotation	
	RMS error	Mean error	RMS error	Mean error	RMS error	Mean error
Position 1	3.1	0.8	3.2	2.0	2.7	0.9
Position 2	3.8	-1.2	2.3	0.9	2.6	1.3
Position 3	4.1	-0.9	2.0	-0.9	3.6	-2.2

**Table 4-3** Hand Behind Back: rms and mean absolute error for the three different positions of HBB.

	Posterior tipping		Upward rotation		Internal rotation	
	RMS error	Mean error	RMS error	Mean error	RMS error	Mean error
Position 1	4.8	0.9	3.0	0.1	3.6	-0.1
Position 2	3.8	-0.1	2.7	-0.3	5.5	1.4
Position 3	4.8	0.3	3.1	-1.3	7.0	-1.1

**Table 4-4** Horizontal Adduction: rms error and mean absolute error for all three positions of H.Add.

	Posterior tipping		Upward rotation		Internal rotation	
	RMS error	Mean error	RMS error	Mean error	RMS error	Mean error
Position 1	5.4	-2.4	4.5	-2.5	4.0	0.6
Position 2	5.3	-2.6	3.3	-1.5	2.2	0.3
Position 3	3.5	-1.9	4.4	-3.6	7.7	6.4

#### 4.4 Discussion

Various techniques based on palpating scapular bony landmarks have been used in the literature (van der Helm and Pronk, 1995; McQuade *et al.*, 1995; Barnett *et al.*, 1999; Lukasiewicz *et al.*, 1999; Meskers *et al.*, 1998). Palpation of bony landmarks does not require prohibitively expensive equipment and is relatively easy to perform. This makes it an attractive method for measuring changes in scapular position.

The hypothesis that the rms error for the digitization method would be less than 5° for each rotation was correct when the full overhead position in abduction was removed from the analysis. The rms errors were 4.5° for posterior tipping, 3.5° for upward rotation, and 4.6° for internal rotation. The rms accuracy of position 3 of the abduction was significantly different from other positions and many of the positions had small differences in mean errors.

The quoted accuracy of this study represents the change in position of the scapula and not the absolute accuracy of measuring scapular position. This is because the gold standard we used relied on an initial digitization process. The accuracy of this process is not known and would require a study that could relate the digitized points to the actual position of the bone.

Another possible limitation was that the bone pins were located fairly close to the posterolateral acromion. This may have made it easier to locate its position. This effect was probably not significant since this was consistently the easiest landmark to find.

This study assumed that the bone pins accurately represented scapular motion. It is possible that skin tension may bend the pins and thus change the position of the optoelectronic markers that were mounted on the pins with respect to the bone. Karduna et al. (Karduna *et al.*, 2001) found that skin tension had negligible affect on the pins both through calculations based on beam theory and cadaver testing. Since we were using the same sized pins and placing them in the same location, skin tension was unlikely to affect the pins in our study.

Sample size in this study was limited to seven subjects. This is an inherent problem in studies using invasive measures. Although the range of ages in the subjects was relatively low (24-36 years), the range in body types was fairly large as signified by the range in the BMI (17-30). Results from this study may not be generalizable to those with higher BMIs due to either large amounts of adipose or muscle tissue.

This study was only able to test the accuracy of this technique and not the reliability. Assessment of the reliability would require that the positions of digitization be strictly controlled. The different positions (1/3, 2/3, full range of motion) in this study were only approximate.

The digitization technique is dependant upon the skill of the measurer for finding the landmarks. All measurements were taken by a single experimenter (D.B., an orthopaedic manual physiotherapist) so the results may not be generalizable to others.

Direct comparison with other studies is difficult because of variation in the techniques used to palpate and digitize the landmarks. In addition, no other study assessed the accuracy of this technique. Several have studied the reliability of digitizing bony landmarks (Barnett *et al.*, 1999; Hebert *et al.*, 2000; Meskers *et al.*, 1998).

Although reliability and accuracy are different aspects of a measurement technique, they are intertwined. When the mean error is close to zero the rms error is almost the same as the standard deviation of the errors. When the rms error is significantly larger than the standard deviation of the errors, the rms error approaches the mean error. Thus if a mean error for a measurement was low, the rms error mostly represents the variability in the errors. When the mean error is larger, the rms error mostly represents the systematic error in the measurement. Test-retest reliability is influenced by variability from a number of sources including variability in the measurement error. Therefore, if the mean error is low and the rms error is similar to the standard deviation of repeated measurements then much of the variability in the repeated measurements is likely due to the measurement error. Because of this relationship between accuracy and reliability, some insight can be gained by comparing our accuracy results to the reliability results from other studies.

The closest study in methodology was Hebert et al. (Hebert *et al.*, 2000). They used an Optotrak probe as well to digitize landmarks. They quoted absolute differences between repeated measurements (reliability) of  $1.6^\circ$  to  $5.9^\circ$  depending on the Euler angle. This was similar in magnitude to the current study's results for accuracy. Assuming that the accuracy of their technique was similar, this suggests that most of the variation is due to difficulty in palpating the landmarks since the accuracy of the optoelectronic camera system is high (0.1mm parallel to the camera, 0.15mm perpendicular to the camera).

For the locator methods (Barnett *et al.*, 1999; Meskers *et al.*, 1998) Meskers et al. reported that intertrial variability ranged from 2.0°-2.5° and interday variability ranged between 3.0°-4.2° while Barnett et al. found the 95% confidence interval to be 4° of rotation. The interday variability measured by Meskers et al. is close to the values for accuracy we measured but their intertrial variability was quite a bit less than our accuracy. The 95% confidence interval of Barnett et al is considerably better than our accuracy measurements but their measurement was based on a series of five measurements. With repeated measurements both the error and the variability would be expected to drop.

Techniques using a locator to palpate all points at once may be more accurate. This would allow the experimenter to ‘weight’ each point based on how confident he was with the position of each landmark. For example, if the experimenter felt that he could very accurately locate the posterolateral acromion and medial root of the scapular spine, he could make sure that the locator lined up with these points exactly. Since the scapula is rigid, the inferior angle mark on the locator would line up properly. Mathematically, it is possible to implement something similar with separate palpations of each point, but the experimenter would have to record a weighting for each point at the time of measurement. The equations could then be modified to account for the different weighting (McCrea, personal communication).

From Figures 4-2 to 4-4 it is apparent that digitization in full abduction is not reliable or accurate. Full abduction had rms errors ranging from 7.3°-12.5°. This was significantly larger than almost every other position for all three angles. This is a position of interest as overhead work is often a contributing factor to shoulder problems. When full abduction is removed from the analysis the errors were very respectable (4.5°, 3.5°, and 4.6°). In full

abduction it is more difficult to palpate the posterolateral acromion because of the bulk of the deltoid. In some subjects it was also difficult to palpate the inferior angle of the acromion in this position. Changes in the overlying tissue thickness would also change the accuracy.

There appeared to be a trend in errors for upward rotation. Positions of lower arm elevation tended to be more positive whereas positions with higher arm elevation tended to be more negative. This was most obvious with abduction, but the H.Add positions also seemed to underestimate upward rotation compared to the first two reaching positions and the HBB positions.

One of the primary goals for measuring scapular motion is to be able to detect differences between subjects with shoulder problems and those without. This will lead to a better understanding of shoulder injuries and hopefully lead to improved diagnostic and treatment regimens. Lukasiewicz et al. (Lukasiewicz *et al.*, 1999) found decreases in posterior tilting between normal subjects and subjects with shoulder impingement at full scaption and 90° of scaption<sup>1</sup>. The difference at full scaption was approximately 9° while the difference at 90° was approximately 7°. Hebert et al. (Hebert *et al.*, 2002) found a difference of 2° of external rotation during flexion in subjects with shoulder impingement. Both studies took an average of two measurements which would decrease the error. With that in mind, all three differences appear to be detectable with the digitization technique.

Because the digitization technique relies on the skill level of the measurer, it brings up an interesting possibility. Additional training may be able to improve accuracy. Having the

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<sup>1</sup> End of range scaption and abduction are almost the exact same position.

measurers practice on many subjects beforehand and locating landmarks under guidance of MRI or ultrasound would probably improve reliability and might improve accuracy.

As mentioned previously, this study assessed the accuracy in measuring the change in scapular position rather than an absolute scapular position. Research still needs to be done to determine the accuracy of digitization in determining the absolute scapular position. More importantly, the digitization method needs to be compared to the orientation of the glenoid fossa which is probably more important than the orientation of the line connecting the medial root of the scapular spine to the posterolateral acromion. It may be appropriate to change the axis system of the scapula. Forming the x-axis from a line connecting the medial root of the scapular spine to the head of the humerus sounds more logical and probably more clinically relevant.

When the accuracy results of this study are combined with the reliability results of other studies, it appears that the digitization of bony landmarks may be a valid method for measuring changes in scapular attitude as long as end of range abduction is avoided. This study helps validate previous studies using this technique.

## **Chapter Five: Accuracy and Reliability of a New Method of Measuring Scapular Kinematics**

### **5.1 Introduction**

Despite recent investigations (Pascoal *et al.*, 2000; Barnett *et al.*, 1999; Hebert *et al.*, 2000; de Groot *et al.*, 1999; McClure *et al.*, 2001; Karduna *et al.*, 2001; Johnson *et al.*, 2001; Karduna *et al.*, 2000; Lukasiewicz *et al.*, 1999), our current knowledge of scapular biomechanics remains limited. There is a need to conduct preliminary studies before realizing the goal of a useful clinical method for measuring scapular movement.

The current gold standards for measuring scapular movement are invasive (Karduna *et al.*, 2001; Choo, 2001). They include roentgen stereophotogrammetric analysis (RSA) and the use of bone pins. RSA involves implanting small metal balls into the bones of interest and then using two x-ray machines to determine the exact location of each of the balls. This method is very accurate but is also invasive, involving surgery to implant the balls as well as exposing the subject to radiation. The use of bone pins involves placing thin metal pins under local anaesthesia such that they are secured in the bone of interest and are protruding out of the skin (McClure *et al.*, 2001). Optoelectronic or electromagnetic sensors can be mounted on the exposed pins to monitor the movement.

Few studies have tried validating non-invasive dynamic methods of measuring three-dimensional movement of the scapula. Two studies have tried to validate the use of an electromagnetic marker (Karduna *et al.*, 2001; McQuade *et al.*, 1998). This marker has either been attached to the acromion of the scapula or to a special jig mounted on the scapula.

McQuade et al. (McQuade *et al.*, 1998) tried to validate the acromial marker method by using two-dimensional x-rays to measure the amount of slippage on a single subject. They found that the skin sensor slipped 4.2mm but did not quote an error in the calculated angle. Furthermore, using a two-dimensional method to validate a three-dimensional method is not appropriate (de Groot, 1999).

Karduna and colleagues (Karduna *et al.*, 2001) validated the use of electromagnetic sensors using a three-dimensional gold standard. They looked at two different methods using skin markers. For one method they used a marker on the skin overlying the acromion. For the other method they used a special tracker which was mounted onto the patient's skin overlying the scapula using the scapular spine as a reference. For validation they used bone pins with the magnetic tracking device to monitor movement. They studied four different movements: humeral elevation in the scapular and sagittal plane, humeral external rotation at 90° of humeral flexion, and horizontal adduction. Overall root mean square (rms) errors ranged from 1.2° to 11.4° depending on the technique (acromial or tracker), the Euler angle, and the movement. The tracker method had the largest error with upward rotation, between 7.2° and 10°. The acromial method had the largest error with external rotation, between 6.2° and 11.4°. In the same study, they developed a correction factor to account for skin movement. This factor was based on the gold standard data from the healthy subjects tested. It reduced the rms error to 4.1° to 4.5° with the tracker method and 2.0° to 4.1° for the acromial method. Unfortunately, when applied to the one subject with shoulder impingement it increased the error of the acromial method. As only 8 subjects were used to develop this correction factor, it has limited generalizability.

Skin correction factors have been developed by other investigators for other areas of the body (Lucchetti *et al.*, 1998; Schmidt *et al.*, 1999; Alexander and Andriacchi, 2001). These techniques generally involved indirect methods of modelling the error caused by movement of the skin with respect to the underlying bone.

Lucchetti et al. (Lucchetti *et al.*, 1998) developed a skin correction factor for the knee. The theory behind their correction factor was that skin movement was due to movement of the joints, and that you could measure the skin movement by moving one joint while keeping the proximal and distal joints stationary. By isolating each of the different joints (i.e. ankle, knee, hip) they could determine the skin deformation caused by each joint. This information could then be used to correct for skin movement during normal movement.

Schmidt et al (Schmidt *et al.*, 1999) used a combination of different methods to correct for skin movement at the elbow. To correct for rotation of the humerus with respect to the skin they decoupled humeral rotation from the humeral markers. They did this by using the orientation of the forearm to measure rotation. As the elbow neared full extension, this method became inaccurate. To overcome this, they fixed the last known reliable measure of the humeral coordinate system at the upper arm markers. To correct for skin movement at the forearm, they measured supination/pronation with a straight wrist. They took the rotation of the hand markers as the actual pronation/supination of the forearm. They compared this movement to that of the forearm markers as a measure of skin movement. They could then use this calibration to correct for skin movement during dynamic movement of the arm.

Alexander et al. (Alexander and Andriacchi, 2001) used a more mathematical method to correct for skin movement when measuring movement at the knee. They used a method

called the point cluster technique. In this technique, a large number of markers are used over the limb. Instead of assuming the markers were a rigid body, they modeled the markers as having a trajectory over the bone as well as having a random noise component. They then placed constraints on the cluster system in order to solve their equations.

It is our belief that a grid of skin markers located over the scapula could be more accurate in describing scapular movement than the methods described previously. The acromial method which Karduna and colleagues tested used only one point to measure movement (Karduna *et al.*, 2001). A grid of markers sampling a greater area of the scapula could theoretically be more accurate. The tracker method has a certain weight to it. This in itself could cause skin movement and decrease the accuracy.

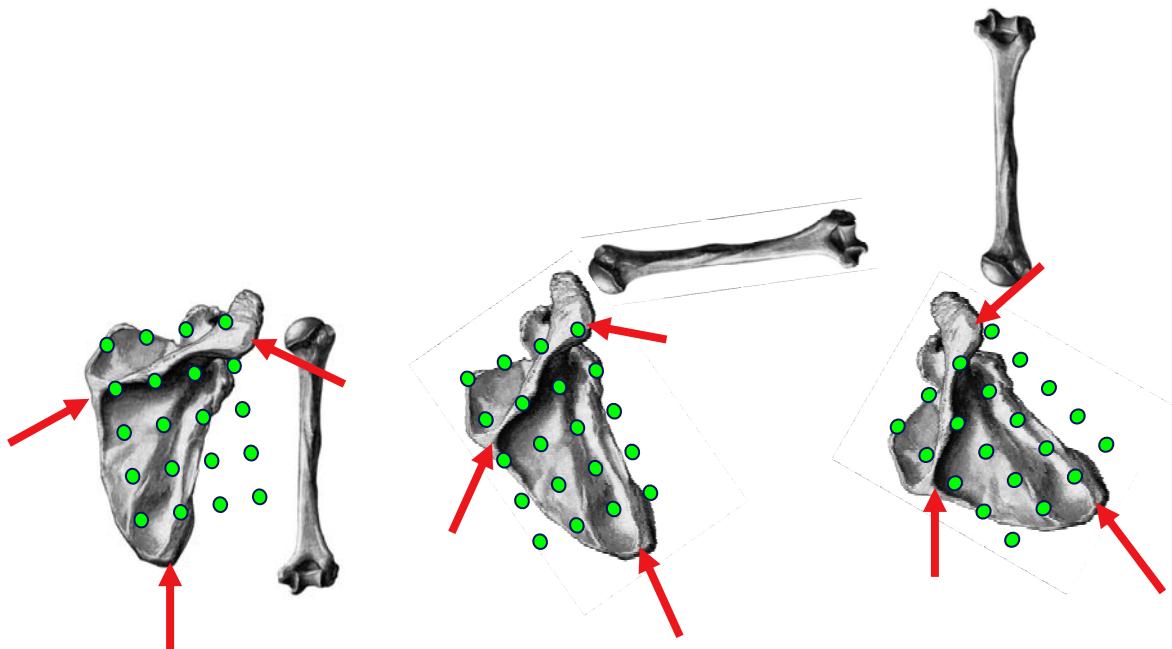
Mr. Anthony Choo (Ph.D. Student) and Dr. Tom Oxland (Director Orthopaedic Engineering Research at Vancouver Hospital and Health Sciences Centre) have developed a method of measuring scapular movement with a grid of skin markers (Figure 5-1) (Choo, 2001). The three-dimensional positions of the markers are monitored with an optoelectronic camera system. Preliminary studies with a cadaver showed that this method has promise with most rotations having rms errors of less than 5°. The theory is that certain combinations of patches will be better at monitoring different rotations, i.e. markers along the length of the scapular spine may describe internal/external rotation well whereas more vertically-oriented markers would be better for monitoring anterior/posterior tipping. As previously discussed, the problem with skin-based measurement systems is slippage of the bone under the skin. Ideally a correction factor would be developed to counter this.



**Figure 5-1** Skin marker grid in neutral and full abduction position.

A correction factor based on normative data would require large numbers of subjects to be involved in a study using one of the gold standards. Considering the invasiveness of the gold standards, this is not feasible. Normative data may not be generalizable to people with shoulder injuries. The optimal solution would be a correction factor based on the subject. If a subject-specific correction factor could be formulated for each subject it would improve our accuracy and would not rely on generalizability across subjects. We propose that the static method of digitizing bony landmarks could be used in a calibration step (the accuracy of this method is reported in chapter 4). First, the skin marker grid would be applied to the subject's shoulder, and then the subject would move their arm to a new position (Figure 5-2). The position of the skin markers would be measured and the bony landmarks digitized again.

This would be repeated at several intervals through the range of motion. If successful, this correction factor could be used for custom movement patterns in future research.



**Figure 5-2.** Movement of markers during movement. This figure shows the scapula at three different arbitrary positions. The skin marker grid is in green and shows some slippage between movements. The red arrows show the bony landmarks which are digitized.

The objective of this study was to determine the reliability and accuracy of this new skin-based method for scapular motion measurement. To examine the reliability, we assessed measurement based on the skin markers over two test days. To assess the accuracy, we compared this method to bone pins which was chosen as our gold standard.

## **5.2 Methods**

### **5.2.1 Subjects**

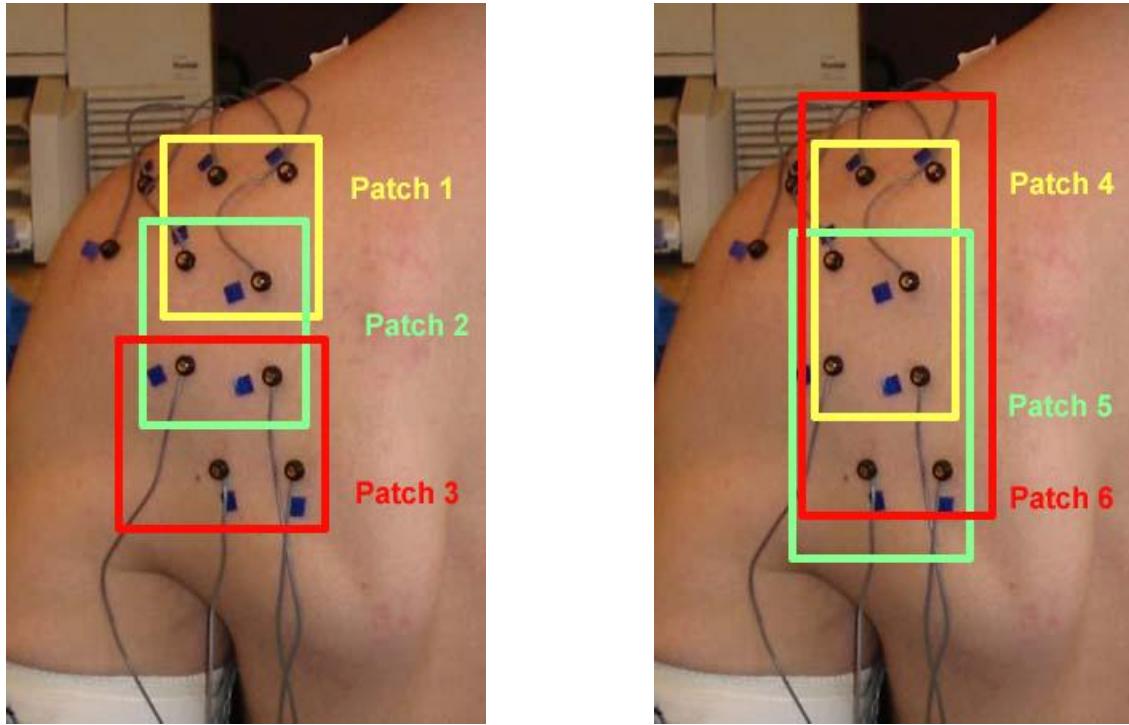
The subjects for this study are the same as described in Chapter 3 on pages 24-25. For brevity, this description is not repeated here.

### **5.2.2 Experimental Protocol**

Testing took place over two days. On the first day subjects had 10 optoelectronic markers placed over the scapula in a 3cmx3cm grid pattern. The first two markers were placed 1.5cm medial to the posterolateral acromion, 1.5cm above and 1.5cm below the scapular spine. The remaining markers were placed such that the first two rows had three markers and the last two rows had two markers (Figure 5-1). The four movements were tested both dynamically (as in Chapter 3) and statically (the digitization method as in Chapter 4). On day 2, the optoelectronic markers were placed as in day one. Each subject was then recorded performing the four movements dynamically again. The bone pins were then inserted as described in Chapter 3. The entire protocol on day one was repeated including the digitization trials. On completion, the pins were removed.

All markers were tracked with an optoelectronic camera system [Optotrak 3020, Northern Digital Inc, Waterloo, ON]. Bone pins were selected as our gold standard over RSA for a number of reasons. Firstly, the pins are temporary. Once the experiment is done, the pins are removed. In RSA, the tantalum balls remain in the body after the experiment (Choo, 2001). Secondly, there is no radiation exposure with the bone pins. Thirdly, previous attempts at using RSA as a gold standard in our lab have failed because of inability to recruit

patients. Finally, the bone pins can be monitored dynamically whereas RSA in our lab can only be monitored statically.



**Figure 5-3** Patch Definitions. Patches 1-3 consist of four LEDs. Patches 4-6 are combinations of the first 3 patches.

### 5.2.3 Data Analysis

The coordinate reference frames and angle sequences for the kinematic analysis of the data were as outlined in Chapters 2 and 3.

#### 5.2.3.1 Skin Correction Factor

The difficulty with measuring scapular motion is that there is considerable sliding of the bone under the skin. When measuring human movement with skin based markers there is the assumption that the skin maintains the same position with respect to the bone. This is not the

case with the scapula. The equation describing the motion of the scapula with respect to the thorax is shown below:

$$T_{tspn\_scapn} = (T_{tspi\_an})^{-1} \times (T_{tspi\_tspn})^{-1} \times T_{scapi\_scapn} \times T_{scapi\_an} \quad (1)$$

Where:  $T_{tspn\_scapn}$  is the transformation matrix describing the intersegmental angle between the scapula and the thoracic spine at time  $n$ .  $T_{tspi\_an}$  describes the transformation between the anatomical reference frame of the thorax and the reference frame of the camera at the initial frame  $i$ .  $T_{tspi\_tspn}$  is the transformation between the thorax markers at time  $n$  and the initial frame  $i$  in the camera's reference frame.  $T_{scapi\_scapn}$  describes the transformation between the scapular markers at time  $n$  and the initial frame  $i$  in the camera's reference frame.  $T_{scapi\_an}$  is the transformation between the anatomical reference frame of the scapula and the camera's reference frame at the initial frame  $i$ .

It was assumed that the thoracic spine (tsp) markers did not move significantly with respect to the thoracic spine and thus the terms in the equation did not need correction and can be ignored for the current discussion.

The  $T_{scapi\_scapn}$  term is the transformation matrix which describes the change in position of the scapular markers from some reference position to a second position in time in the global reference frame. The axis system is coincident with the axis of the camera. This is not useful on its own because it does not describe how the scapula was positioned in the camera's axis system. The  $T_{scapi\_an}$  term describes this. Bony landmarks are digitized on the scapula and these points are used to calculate the transformation between the axis system of the global reference frame and that of the scapula.

If the skin stays in the same position with respect to the bone, the actual  $T_{scapi\_an}$  term remains the same throughout movement. It is thus valid to measure this in one position. If there is movement of the skin with respect to the scapula, the real value of  $T_{scapi\_an}$  changes and therefore it is not valid to calculate this transformation in only one position of the scapula. Another key point is that the reference position used in calculating  $T_{scapi\_scapn}$  must be the same one used in calculating  $T_{scapi\_an}$ . This means that measurement of  $T_{scapi\_an}$  in a second position would require a new calculation of  $T_{scapi\_scapn}$ . These concepts are the basis for the skin correction factor. The skin correction factor works by calculating  $T_{scapi\_an}$  and  $T_{scapi\_scapn}$  for several different reference positions throughout the range of motion. The resulting Euler angles can then be combined as described below to correct for skin movement.

For each movement seven different positions were digitized throughout the range. Each of these seven positions was used as the reference frame to calculate  $T_{tspn\_scapn}$  and the resulting joint angles. This gives seven different sets of joint angles for each movement. The question now becomes how to combine the different joint angles to come up with the most accurate result. Each of the different series of joint angles is theoretically most accurate when in the same position as where the reference frame (digitization) was taken. The seven movements were combined so that each was weighted more heavily when close to its reference position.

To determine how close a position was to a particular reference frame, the angle of the humerus (elevation for abduction and reaching, rotation for HBB and H.Add) was compared to the angle of the humerus when the reference frame was taken. A coefficient for that reference frame was calculated using equation 2 where  $C_{refi\_n}$  is the coefficient for reference frame  $i$  at time  $n$ ,  $H_{refi}$  is the humeral angle of reference frame  $i$ , and  $H_n$  is the humeral angle at time  $n$ . Notice that the  $C_{refi\_n}$  will be highest when  $H_{refi}$  and  $H_n$  are the same and 0 when

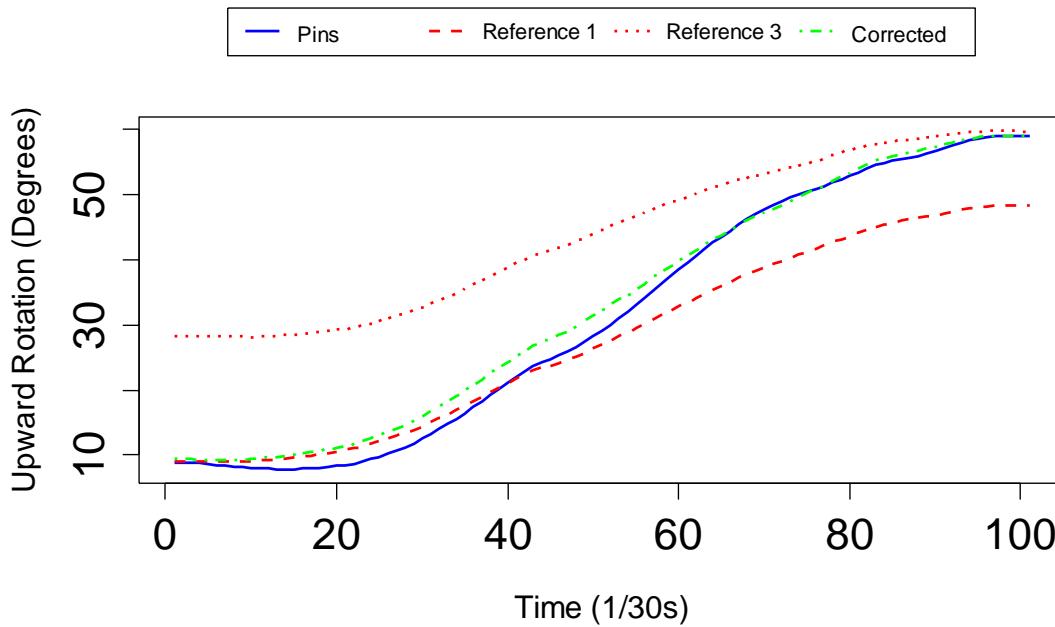
$100^\circ$  apart. In order to prevent a negative coefficient,  $C_{refi\_n}$  was set to 0 when  $|H_{refi} - H_n|$  was greater than 100.

$$C_{refi\_n} = 1 - \frac{|H_{refi} - H_n|}{100} \quad (2)$$

Equation 3 was then used to calculate the corrected joint angles, where  $Ang_{cor\_n}$  is the set of angles (i.e. thoracic, humeral, and scapular patches) at time n, and  $Ang_{refi\_n}$  is the set of angles calculated using reference frame  $i$ . The end result is an average of all the reference frames weighted towards the reference frames taken closest to the current position.

$$Ang_{cor\_n} = \frac{\sum_i (C_{refi\_n} \times Ang_{refi\_n})}{\sum_i C_{refi\_n}} \quad (3)$$

A simplified example for two reference frames is shown in Figure 5-4. This graph was taken during abduction with one of the subjects. Reference frame one is most accurate in the left portion of the graph while reference frame three is most accurate on the right side of the graph. Reference frame one was taken with the arm in the same position as point 0. Reference frame three was taken with the same arm in the same position as point 100. If reference frame one is weighted more heavily on the left side of the graph and reference frame 3 on the right, the resulting curve (i.e. corrected) is very similar to the pins.



**Figure 5-4** Sample data demonstrating the effect of the skin correction factor. Reference frame one was taken at time 0. Reference frame 3 was taken at time 100. The corrected line is a combination of reference frame one and two weighted towards reference frame one at the beginning of motion and reference frame two at the end of the motion.

To determine accuracy, the corrected angles need to be compared with a gold standard. The bone pins that were used as a gold standard relied on a digitization process to provide the transformation to the scapula's anatomical reference plane. In theory, any of the seven different digitization positions could have been used because the pins did not move with respect to the scapula. To minimize the error, the average of all seven digitizations was used. There was an exception for the abduction movement. The two full abduction positions were removed from calculating both the gold standard and corrected movement. This was because of the poor digitization accuracy of this position (Chapter 4).

### 5.2.3.2 Effect of Pins

To calculate the effect of the pins on skin movement, a root mean squared (rms) difference was calculated between the patches on day 2 before the pins and the patches on day 2 with the pins. Intraclass correlation coefficients (ICC(3,10)) were also calculated between the two sets of movements on day 2. The rms difference and the calculated ICCs are a product of both the same day reliability and the effect of the pins. To help to separate the two components, the rms differences and ICCs with and without the pins were compared to the ICCs and rms differences calculated in Chapter 3 for same day reliability with the pins. The closer these values were together, the smaller the effect of the pins.

### 5.2.3.3 Cross Correlation

Cross correlation is a method of determining the similarity between two signals, or time series data (Winter and Patla, 1997). It involves calculating a Pearson product moment coefficient between each signal, shifting one signal either forwards or backwards in time and then recalculating the Pearson product moment coefficient. The end result is a series of correlation coefficients. If there is a phase shift between the coefficients, the highest correlation will be for one of the shifted signals. It can thus be used to measure a time delay between the signals.

To help determine the validity of the patches a cross correlation was first performed between the patches and the pins to assess if movement of the patches represented the movement of the scapula itself. A high correlation would not mean that the patches were accurate but that any error was highly systematic and thus correctable.

#### **5.2.3.4 Accuracy**

RMS errors were calculated between the pins and the patches and between the pins and the corrected patch movement. A two way repeated measures ANOVA was done to see if there were significant differences between patches. Type of movement and patch were the factors. If the Huynh Feldt epsilon was less than 0.7, it was deemed that the sphericity assumption was violated and an adjusted p value was then used. Tukey's HSD was used for posthoc testing. A p value of 0.05 was deemed significant.

#### **5.2.3.5 Reliability**

Reliability of the patches was assessed by calculating ICC(3,10) values for each humeral angle for each movement. Comparisons were made between the corrected day 1 patches and the corrected day 2 patches. An rms difference was also calculated between the corrected day 1 patches and corrected day 2 patches (with the bone pins). A two way repeated measures ANOVA was performed to determine if there were differences in reliability between the patches or movements. As with accuracy, the p values were adjusted if the sphericity assumption was violated. Between the accuracy and the reliability calculations a total of six two-way ANOVAs were performed. As with the accuracy analysis, Tukey's HSD was used for posthoc testing.

### **5.3 Results**

The data from one subject was rejected from the study due to a loosened bone-pin interface (refer to Chapter 3).

### 5.3.1 Effect of Pins

RMS differences between the patches with the pins in and the patches without the pins ranged from 1.1-5.0° (Table 5-1). This compares favourably with the rms differences (1.1-4.7°) from two trials done with the pins in and better than the rms differences (3.3-7.6°) between day one and day two (Table 5-4).

**Table 5-1** Comparing RMS differences of patch 4 with pins and patch 4 without pins to same day. The same day reflects the rms difference between two trials with pins in. Patch w/wo pins reflects the rms difference between a trial with the pins in and a trial without the pins.

	Posterior tipping		Upward rotation		External rotation	
	Same Day	Patches w/wo pins	Same Day	Patches w/wo pins	Same Day	Patches w/wo pins
Abduction	1.9	4.1	1.2	1.6	2.0	4.0
Reaching	4.0	3.4	2.8	1.1	3.9	3.4
Hand Behind Back	2.0	2.8	4.7	2.2	3.3	2.0
Horizontal Adduction	1.7	4.0	1.1	2.2	2.1	5.0

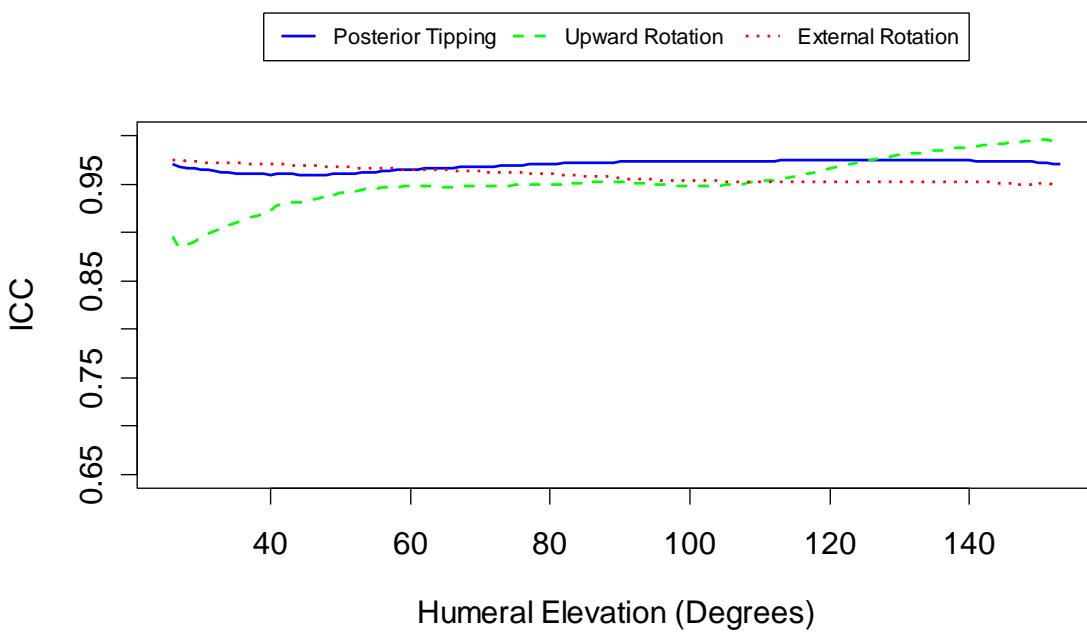
The ICCs for the patches with pins and the patches without pins are based on the data from six subjects. This is because we had to adjust the arm band on the first subject after the pins were put in. This meant that we could not use the reference frame taken with the pins in to calculate angles for trials before the pins were put in.

For abduction the ICCs stayed above 0.95 for the entire range of movement for posterior tipping and external rotation. For upward rotation it started above 0.88 and climbed to close to 1 at the end of range (Figure 5-5).

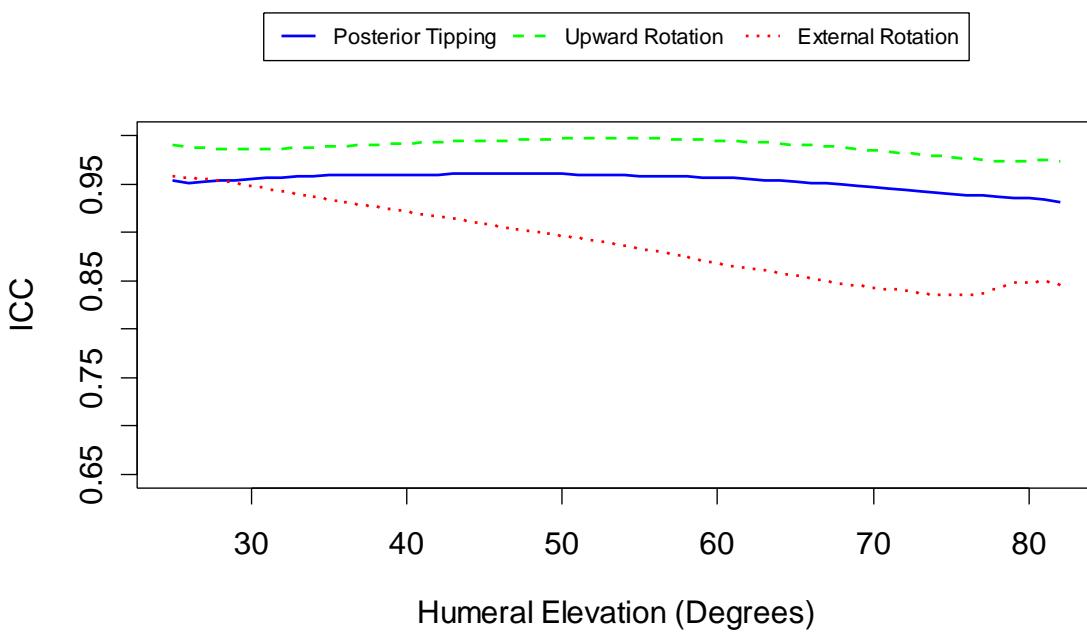
For reaching, the ICCs stayed at approximately 0.95 for posterior tipping, close to 1.0 for upward rotation, and for external rotation started above 0.95 and decreased to below 0.85 at the end of range (Figure 5-6).

For HBB the ICCs for posterior tipping stayed above 0.94 throughout range, while the ICC for external rotation and upward rotation started and finished above 0.94 but dropped close to 0.90 near the middle of range (Figure 5-7).

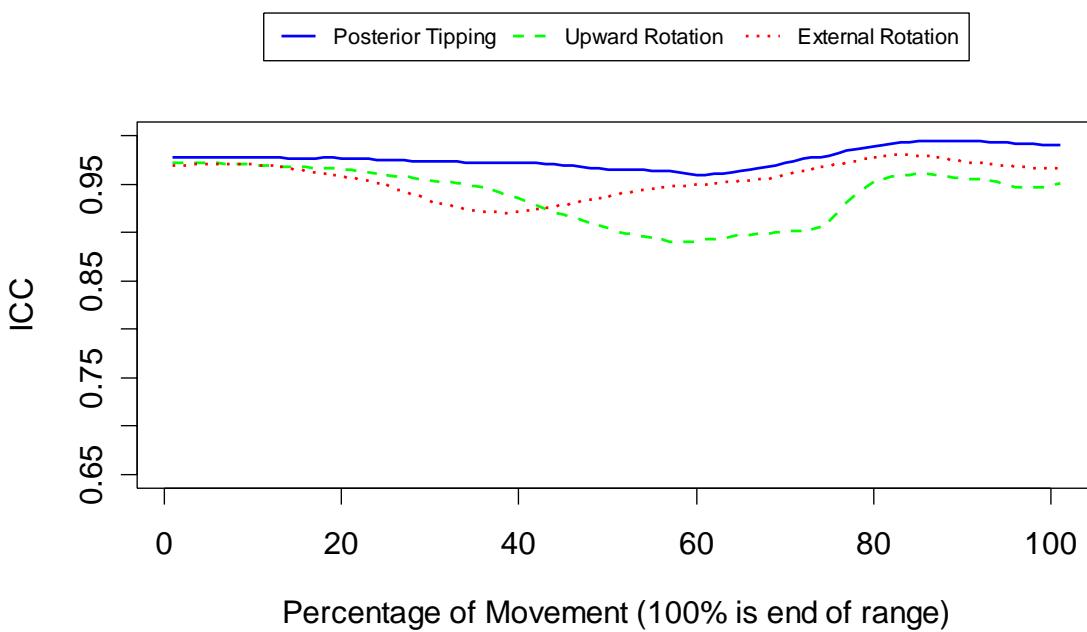
Finally for H.Add, the ICCs for posterior tipping and upward rotation stayed above 0.94 for the entire range while the ICC for external rotation stayed between 0.68 and 0.80 throughout the range of motion (Figure 5-8).



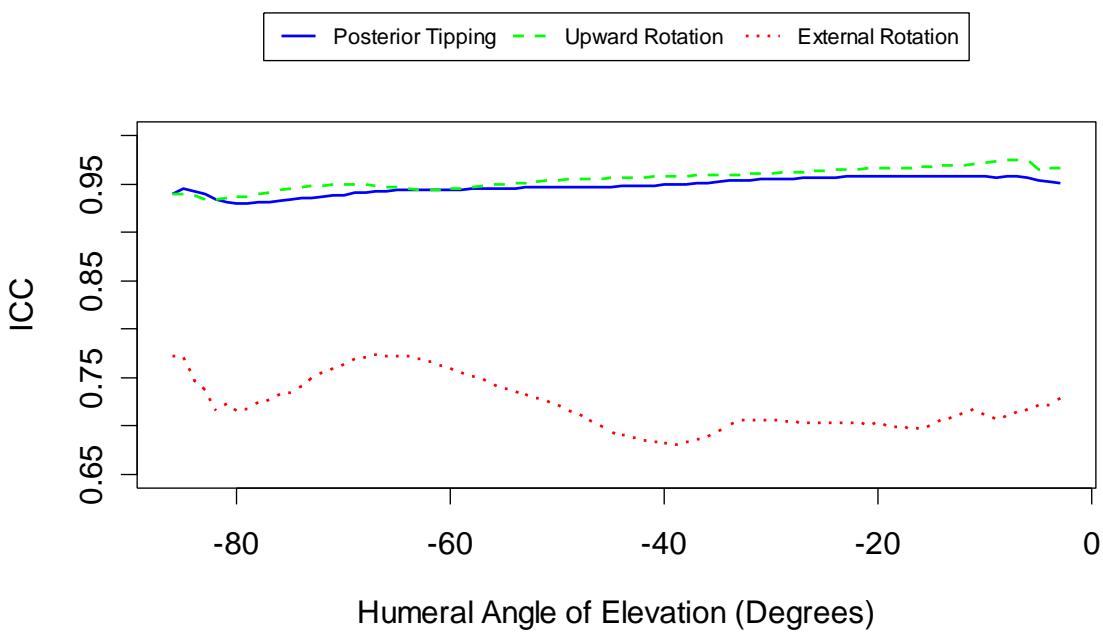
**Figure 5-5** Abduction. ICC comparing patch 4 with pins and patch 4 without pins.



**Figure 5-6** Reaching. ICC comparing patch 4 with pins and patch 4 without pins



**Figure 5-7** Hand Behind Back ICCs comparing patch 4 with pins and patch 4 without pins



**Figure 5-8** Horizontal Adduction ICCs comparing patch 4 with pins and patch 4 without pins.

### 5.3.2 Cross Correlation

The cross correlation between the patches and the pins ranged from 0.68-0.99 (Table 5-2). HBB was consistently the lowest ranging from 0.68-0.88 while H.Add was consistently the highest ranging from 0.95-0.99. The overall average was very similar between the patches with the lowest being patch 1 at 0.87 and the highest being patches 2, 5 and 6 at 0.93. All cross correlation values were taken at zero lag because the subject specific correction factor does not correct for lag. Lag indices indicated if there was a phase shift between the patches and pins (Winter and Patla, 1997). Examination of the lag indices showed that most of the lags were zero or very close to zero.

**Table 5-2** Cross correlation between pins and patches.

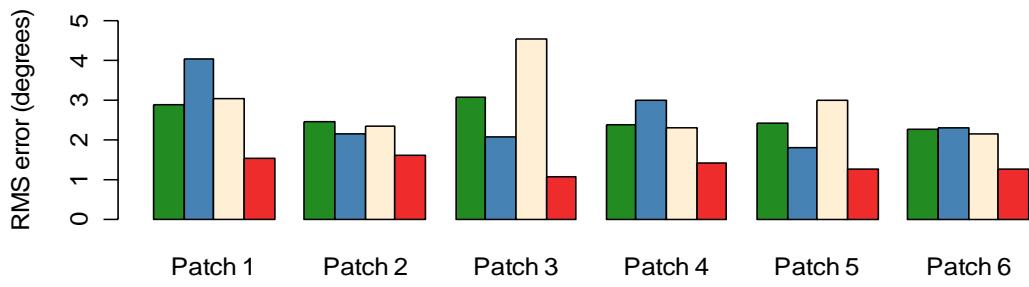
	Patch 1	Patch 2	Patch 3	Patch 4	Patch 5	Patch 6
Abduction	0.96	0.94	0.86	0.96	0.91	0.94
Reaching	0.87	0.95	0.90	0.93	0.93	0.93
HBB	0.68	0.84	0.81	0.79	0.88	0.87
H.Add	0.95	0.99	0.98	0.99	0.99	0.99
Overall average	0.87	0.93	0.89	0.92	0.93	0.93

### 5.3.3 Accuracy

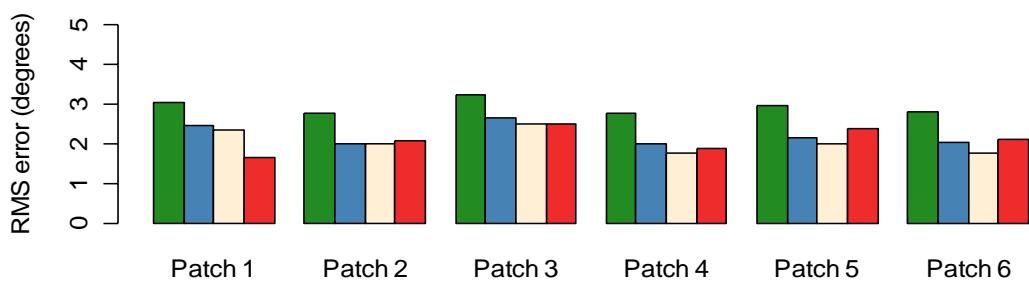
The rms errors for the different patches and different movements are shown in Figure 5-9. These values have been corrected with the skin correction factor. To determine if any of these differences were significant a two way repeated measures ANOVA was performed with movement and patches as factors.

For posterior tipping, there was a main effect of movement ( $p=0.003$ ), a main effect of patch ( $p<0.002$ ) and an interaction ( $p<0.0001$ ). Posthoc analysis using Tukey's HSD showed that patches 6 (mean= $1.9^\circ$ ), 2 (mean= $2.0^\circ$ ), 5 (mean= $2.0^\circ$ ) and 4 (mean= $2.1^\circ$ ) had significantly smaller errors than patches 1 (mean= $2.7^\circ$ ), and 3 (mean= $2.6^\circ$ ). For the main effect of movement, H.Add (mean= $1.3^\circ$ ) had a significantly smaller error than HBB (mean= $2.9^\circ$ ) and abduction (mean= $2.5^\circ$ ). A simple main effects analysis of the interaction showed that there was no difference between the rms errors for the different patches in abduction (Figure 5-10). For reaching, patch 1 was worse than patches 2, 3, 5 and 6. For HBB patch 3 had larger errors than every other patch and patch 1 was worse than patch 6. There were no statistical differences between the errors of the different patches during H.Add.

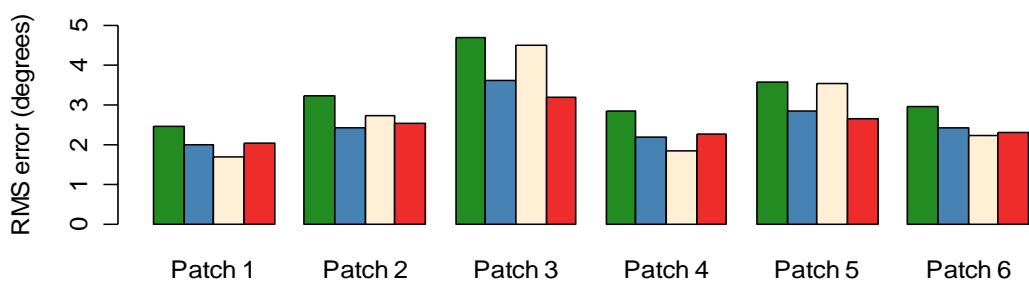
### Posterior Tipping



### Upward Rotation

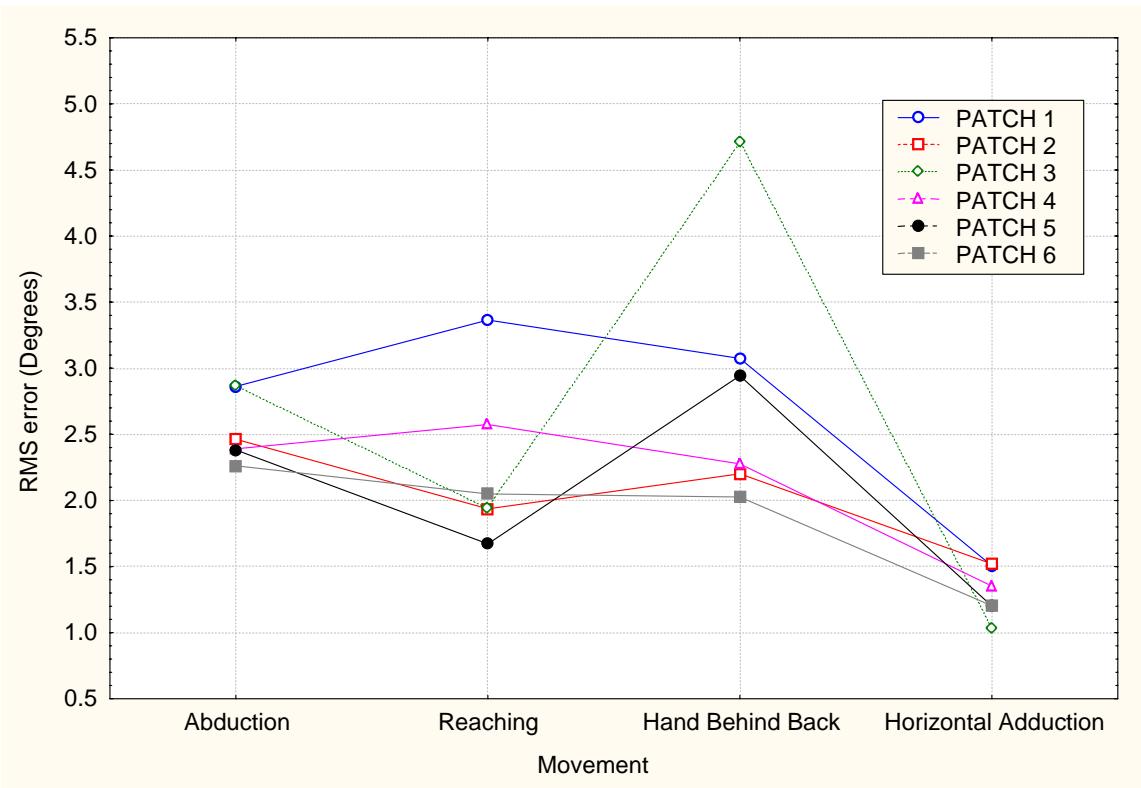


### External Rotation



█ Abduction      █ Reaching      █ Hand Behind Back      █ Horizontal Adduction

**Figure 5-9** RMS errors for the corrected patches for posterior tipping, upward rotation and external rotation



**Figure 5-10** Posterior tipping: interaction between movement and patch. Movement levels: 1 Abduction, 2 Reaching, 3 Hand Behind Back, 4 Horizontal Adduction.

For upward rotation there was a main effect of patch ( $p=0.04$ ). Patches 4 (mean= $2.0^\circ$ ), 6 (mean= $2.0^\circ$ ) and 2 (mean= $2.0^\circ$ ) were significantly more accurate than patch 3 (mean= $2.5^\circ$ ).

For external rotation there was a main effect of patch ( $p<0.0001$ ) and a significant interaction ( $p=0.001$ ). Graphical analysis revealed that the interaction only affected the least accurate patches and thus was not of interest. Posthoc analysis of the main effect of patch showed that patch 1 (mean= $1.9^\circ$ ) was significantly more accurate than patches 2 (mean= $2.6^\circ$ ), 3 (mean= $3.8^\circ$ ), 5 (mean= $3.0^\circ$ ), and 6 (mean= $2.4^\circ$ ). Patch 4 (mean= $2.1^\circ$ ) was significantly more accurate than patches 2, 3, and 5. Patch 2 was significantly more accurate than patches 3 and 5 but significantly less accurate than patches 1 and 4 (mean= $2.1^\circ$ ). Patch 3 was significantly

worse than every other patch while patch 5 was significantly worse than every patch except 3.

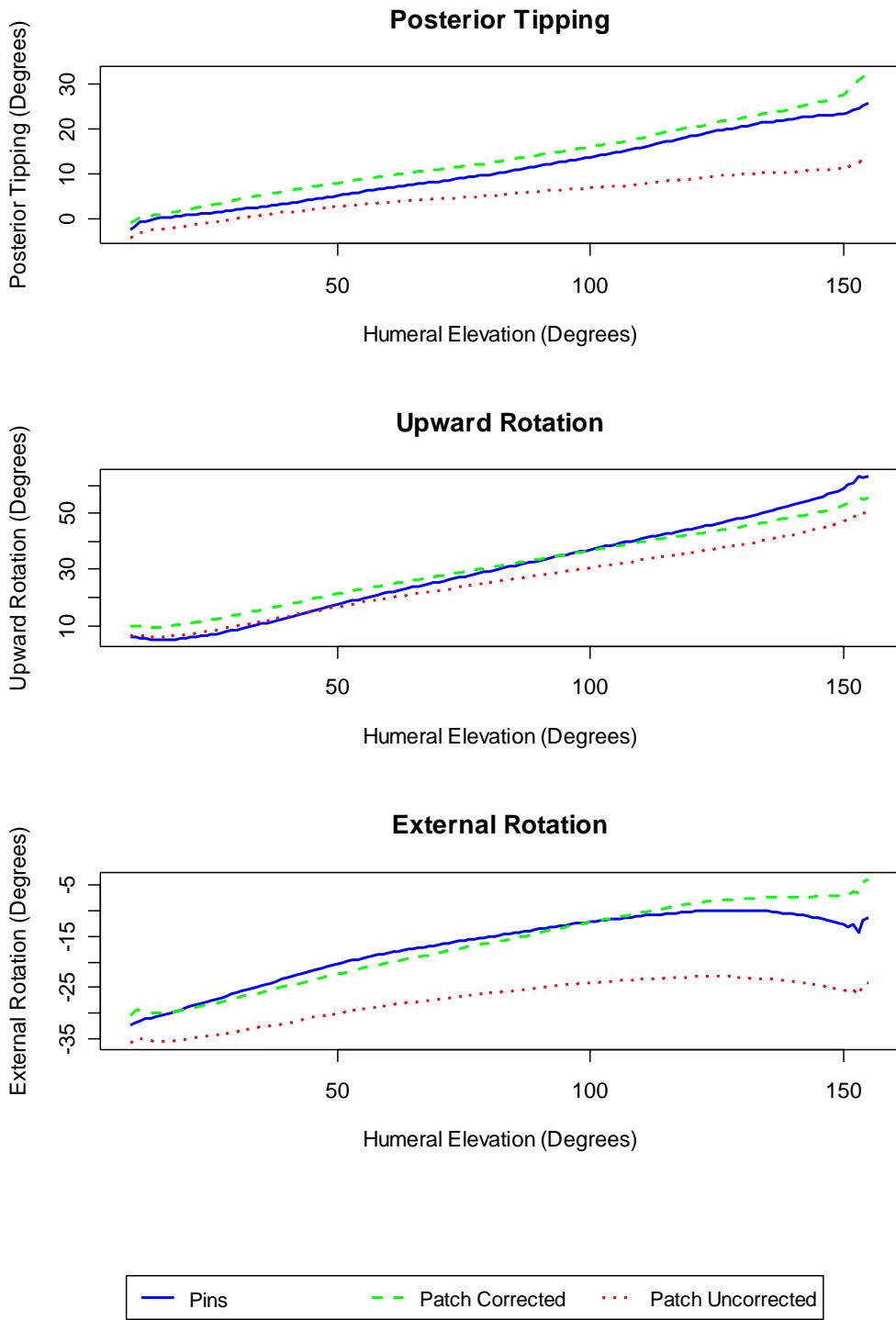
For brevity most of the Figures in this section will be based on patch 4. Patch 4 was the only patch which was not significantly different from the best patch for all three rotations. The rms errors for patch 4 without the correction factor ranged from  $5.1^\circ$ - $9.5^\circ$  while the rms errors for patch 4 with the correction factor ranged from  $1.4^\circ$  to  $3.0^\circ$  (Table 5-3).

Figures 5-11 through 5-14 are examples comparing the pins to the corrected and uncorrected patch 4 for various subjects. Although there were differences between subjects, these figures were chosen to be fairly typical rather than best case. The graphs for all subjects and all movements are available in Appendix E.

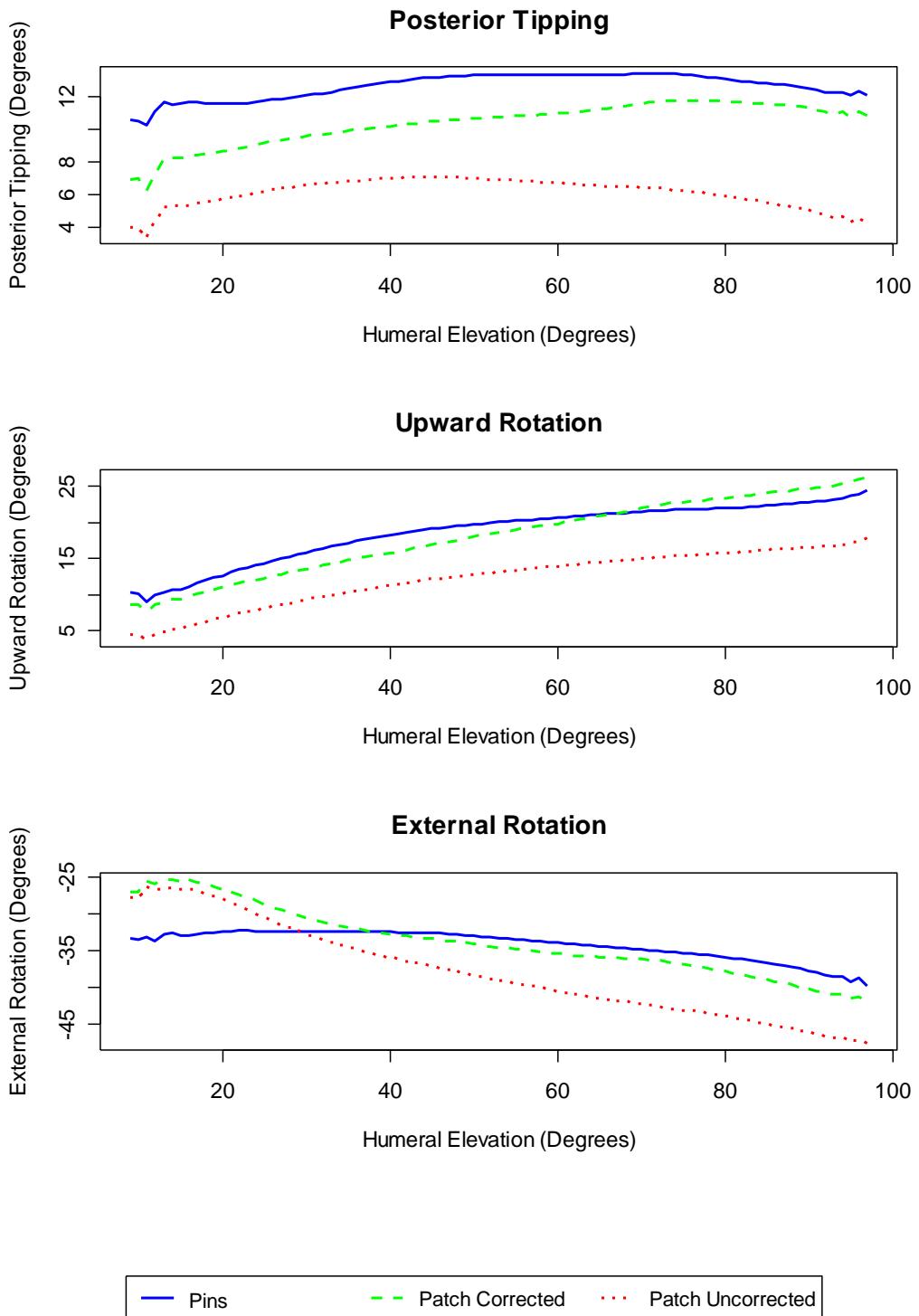
During abduction for subject 3 the corrected patch followed the pins very closely for posterior tipping while the error from the uncorrected patch increased throughout the range (Figure 5-11). For this same subject, upward rotation stayed very similar for all three lines throughout the range of motion. Little correction was needed in this instance. The corrected patches represented external rotation much better than the uncorrected patch.

**Table 5-3.** RMS errors for Patch 4 corrected and uncorrected with standard deviations (degrees).

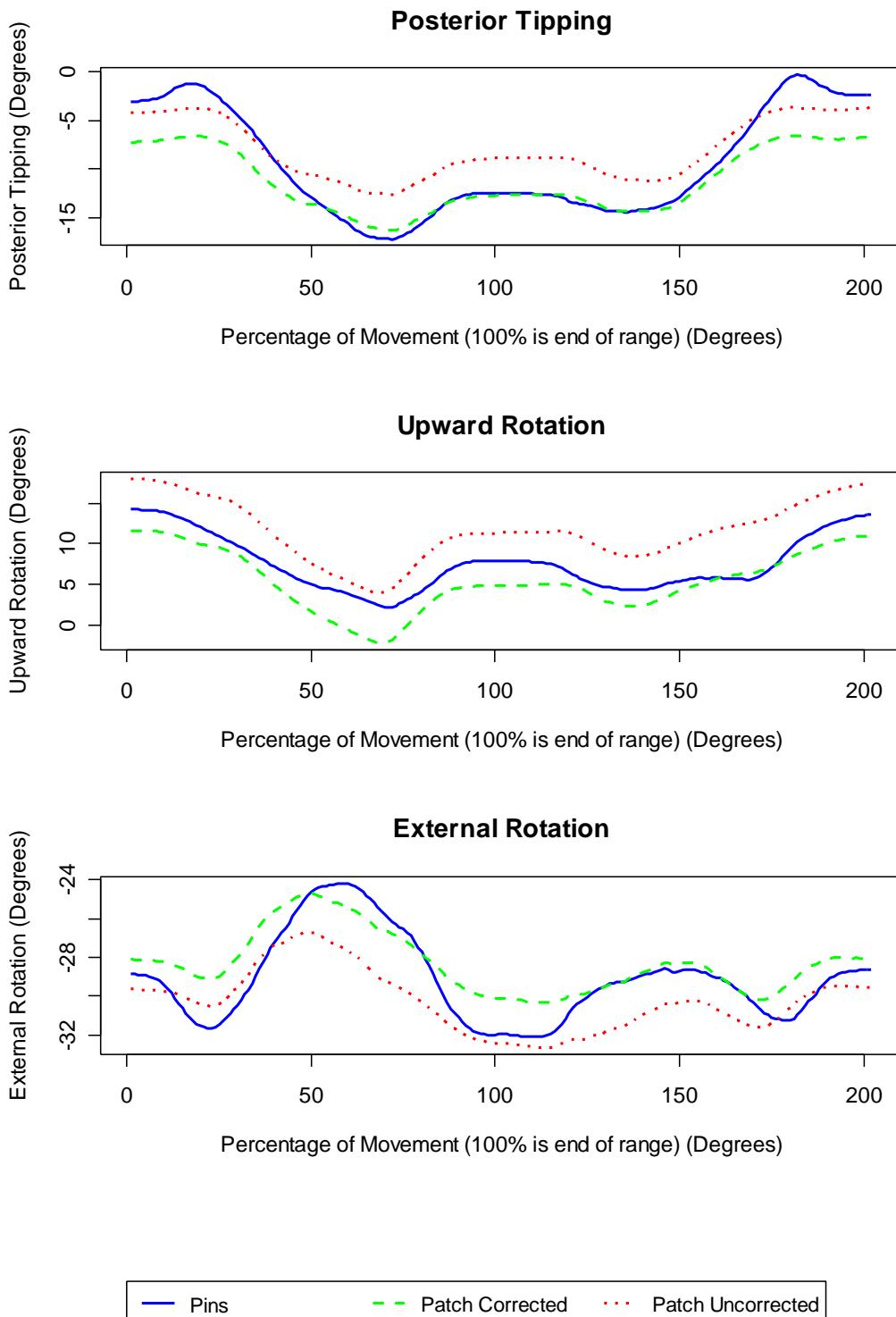
	<b>Posterior Tipping</b>		<b>Upward Rotation</b>		<b>External Rotation</b>	
	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
Abduction	$9.7 \pm 4.3$	$2.4 \pm 0.3$	$7.5 \pm 0.8$	$2.8 \pm 0.8$	$9.5 \pm 3.6$	$2.8 \pm 0.6$
Reach	$5.1 \pm 3.0$	$3.0 \pm 1.4$	$4.2 \pm 2.0$	$2.0 \pm 0.8$	$6.0 \pm 2.5$	$2.2 \pm 0.9$
HBB	$9.7 \pm 6.7$	$2.3 \pm 0.5$	$7.8 \pm 4.7$	$1.6 \pm 0.7$	$5.1 \pm 3.4$	$1.8 \pm 0.5$
H.Abd	$4.8 \pm 1.5$	$1.4 \pm 0.6$	$6.4 \pm 2.5$	$1.9 \pm 0.8$	$7.0 \pm 1.0$	$2.3 \pm 0.7$



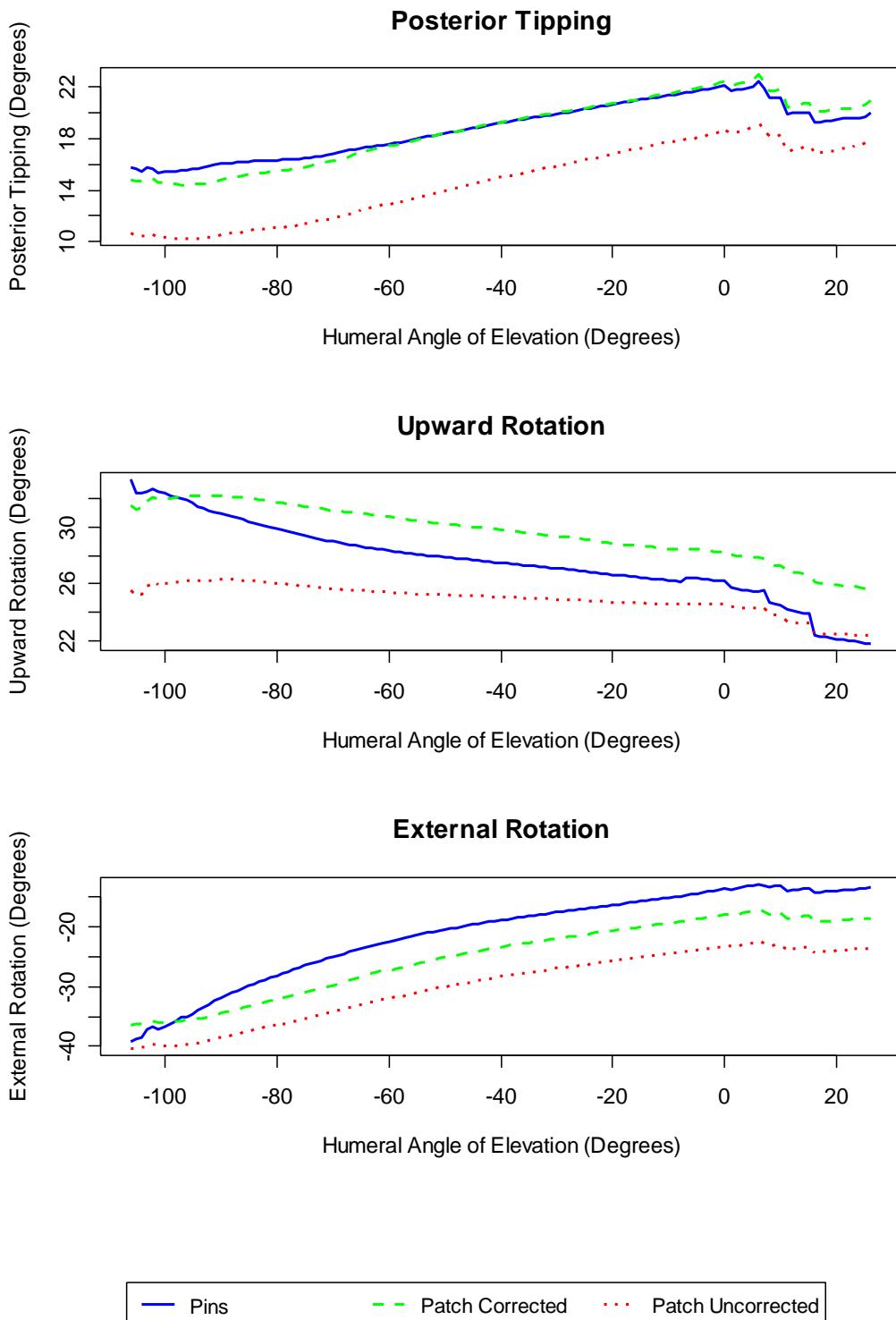
**Figure 5-11** Abduction: Comparison of pins versus corrected and uncorrected patches for posterior tipping, upward rotation and external rotation (subject 3).



**Figure 5-12** Reaching: Comparison of pins and corrected and uncorrected patches for posterior tipping, upward rotation and external rotation (subject 7).



**Figure 5-13** Hand Behind Back: Comparison of pins and corrected and uncorrected patches for posterior tipping, upward rotation and external rotation (subject 4).



**Figure 5-14** Horizontal Adduction: Comparison of pins and corrected and uncorrected patches for posterior tipping, upward rotation, and external rotation. (subject 1).

For reaching in subject 7, the corrected patch got closer to the pins near the end of range while the uncorrected patch stayed a constant distance away from the pins (Figure 5-12).

Upward rotation was represented better by the corrected patch than the pins. For external rotation both the uncorrected and corrected patches started off with the same error, approximately  $7^\circ$  but the corrected patch closed the gap and followed the pins closely through range.

For HBB in posterior tipping, the uncorrected patch was more accurate at the start of movement but by 50% of the range the corrected patch closely followed the pins (Figure 5-13). The overall range of motion was small at around  $15^\circ$ . For upward rotation and external rotation the corrected patch was sometimes more accurate and sometimes less accurate throughout the range.

Figure 5-14 shows an example subject for H.Add. For posterior tipping the corrected patch followed the pins almost exactly while there was an offset for the uncorrected patch. For upward rotation the uncorrected patch started closer to the pins but the corrected patch was more accurate by the end of range.

### **5.3.4 Reliability**

The rms differences between day one and day two for all angles and movements ranged from  $3.8-7.5^\circ$  (Table 5-4).

For the rms differences in posterior, tipping there was not a significant main effect for patch or movement but there was a significant interaction ( $p<0.0001$ ). A graphical analysis of the interaction showed that it was not of interest since it affected the least accurate patches.

None of the differences in the reliability of upward rotation were significant.

For external rotation, there was a main effect of patch ( $p<0.0001$ ) and a significant interaction ( $p=0.008$ ). Graphical analysis of the interaction showed that it affected the least accurate patches and thus was not of interest. Posthoc analysis (Tukey's HSD) of the main effect of patch showed that patch 1 (mean= $5.5^\circ$ ) was significantly more reliable than patches 2 (mean= $6.0^\circ$ ), 3 (mean= $6.6^\circ$ ) and 5 (mean= $6.2^\circ$ ). Patch 2 (mean= $6.0^\circ$ ) was significantly more reliable than patch 3. Patch 3 was significantly less reliable than every other patch except patch 5. Patch 4 (mean= $5.7^\circ$ ) was significantly more reliable than patches 3 and 5.

**Table 5-4** RMS difference between day 1 and day 2 corrected movements for patch 4.

	<b>Posterior tipping</b>	<b>Upward rotation</b>	<b>External rotation</b>
Abduction	$4.2 \pm 0.4$	$6.2 \pm 3.4$	$7.5 \pm 3.7$
Reaching	$3.8 \pm 2.9$	$3.9 \pm 1.9$	$7.3 \pm 3.5$
Hand Behind Back	$5.2 \pm 2.3$	$4.7 \pm 2.7$	$7.2 \pm 3.5$
Horizontal Adduction	$5.4 \pm 3.0$	$5.1 \pm 2.9$	$5.6 \pm 3.1$

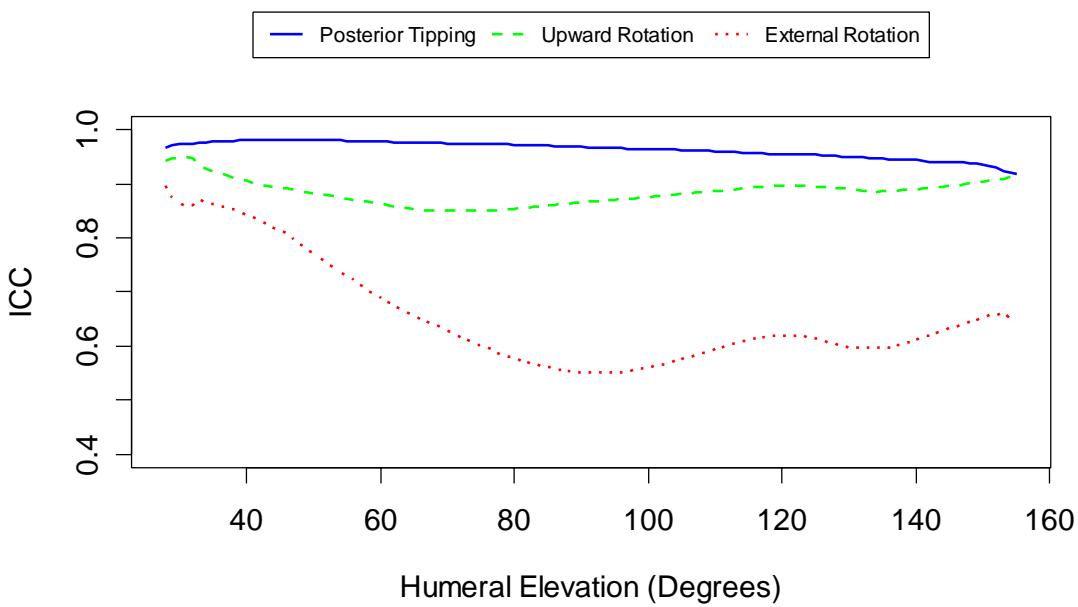
In abduction the ICCs for posterior tipping and upward rotation stayed well above 0.85 throughout the range while external rotation started at about 0.9 but decreased to under 0.6 at around  $80^\circ$  and hovered around 0.6 for the rest of the motion (Figure 5-15).

In reaching, the ICC for posterior tipping started above 0.84 and climbed to 0.9 while upward rotation started above 0.89 and climbed to close to 0.96 (Figure 5-16). The ICC for external rotation stayed relatively constant above 0.84 through the range of motion.

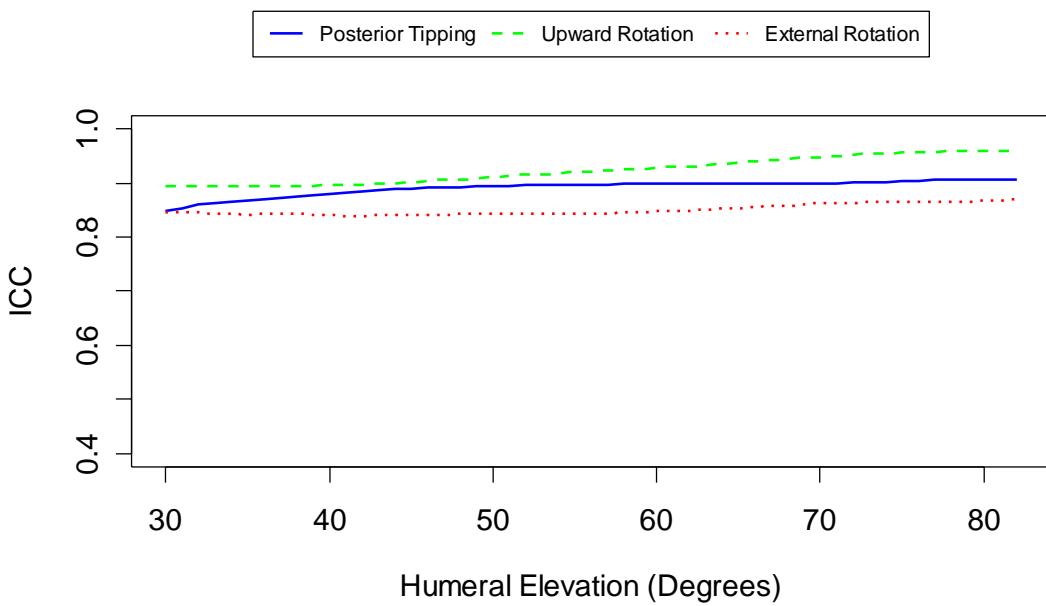
When putting the hand behind back, posterior tipping was very reliable with ICCs staying above 0.9 (Figure 5-17). Upward rotation started above 0.8 but dipped down to 0.5 halfway through movement before climbing above 0.7 at the end of the range. External rotation started at around 0.6 and climbed up to 0.8.

The ICCs for posterior tipping during H.Add ranged from 0.6 to close to 0.9 while the ICCs for upward rotation stayed close to 0.9 throughout the range (Figure 5-18). The ICCs for external rotation started at close to 0.5, climbed over 0.7 for most of range and then dropped close to 0.6 near the end of the range.

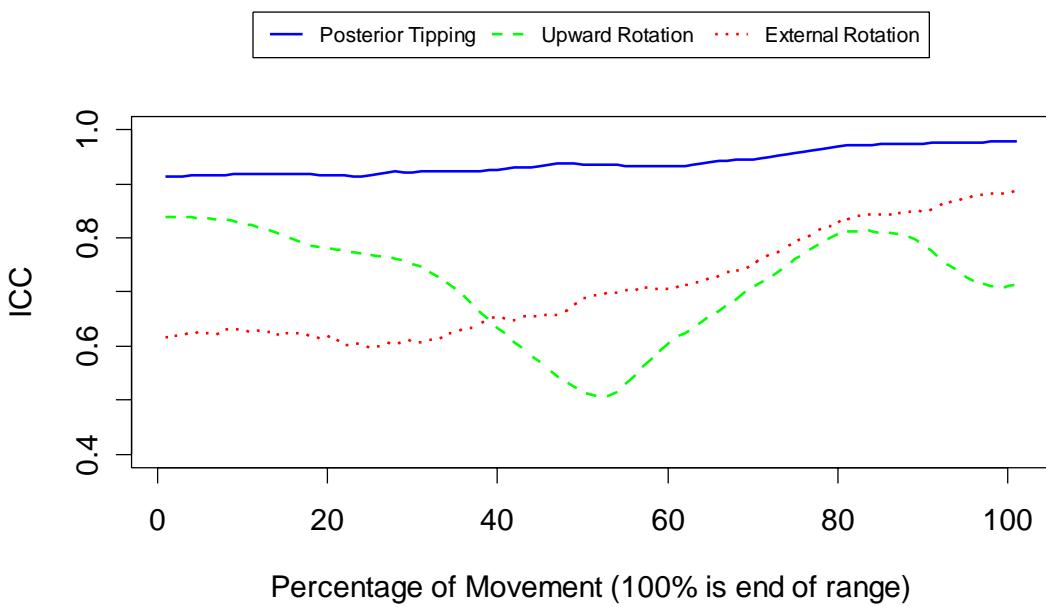
Figures 5-19 to 5-22 show examples of day to day reliability of these movements. Most showed very similar slopes and overall values. There was a fairly substantial offset noticeable in HBB (Figure 5-21). This may help explain the lower reliability of this movement.



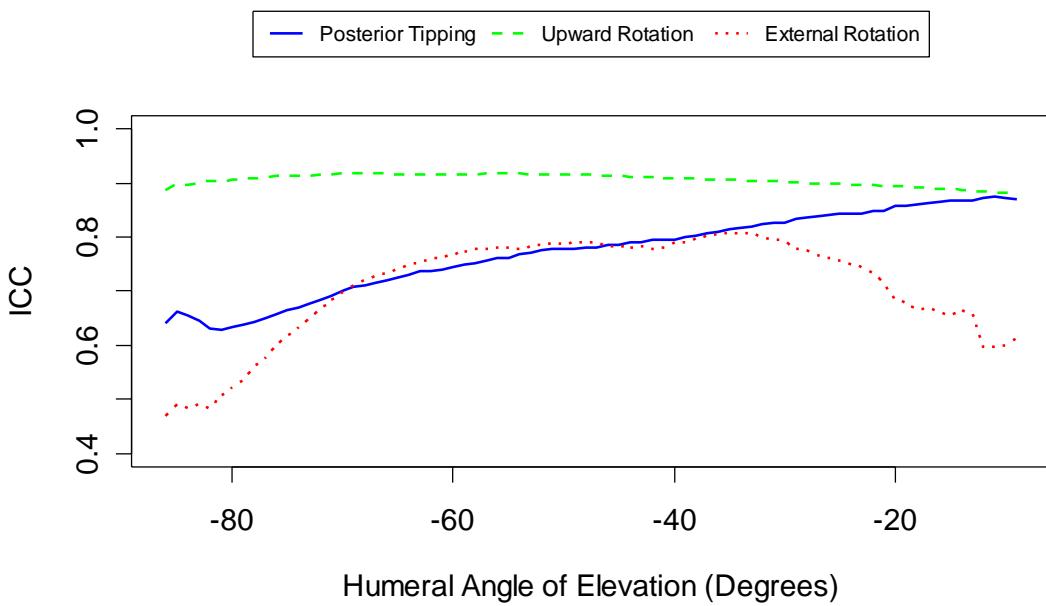
**Figure 5-15** Abduction: ICC(3,10) throughout the range of humeral elevation.



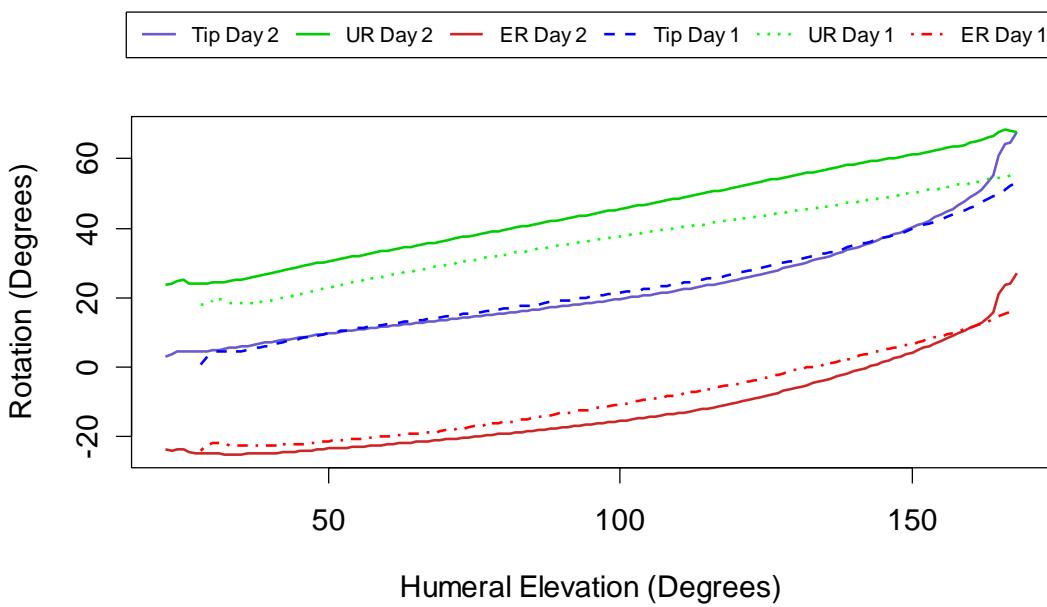
**Figure 5-16** Reaching: ICC(3,10) throughout the range of humeral elevation



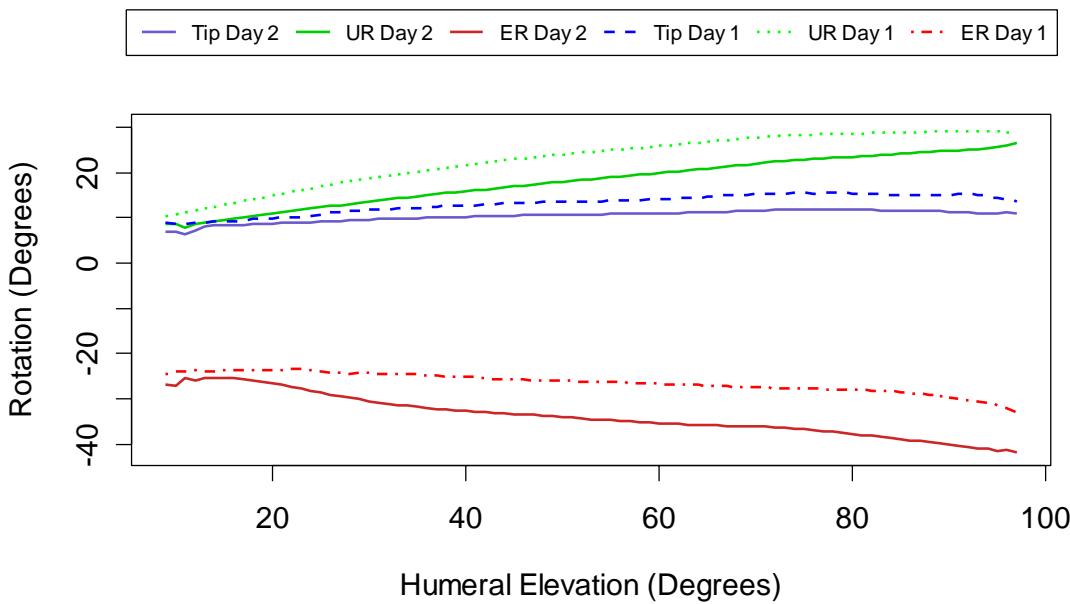
**Figure 5-17** Hand Behind Back: ICC(3,10) throughout the movement.



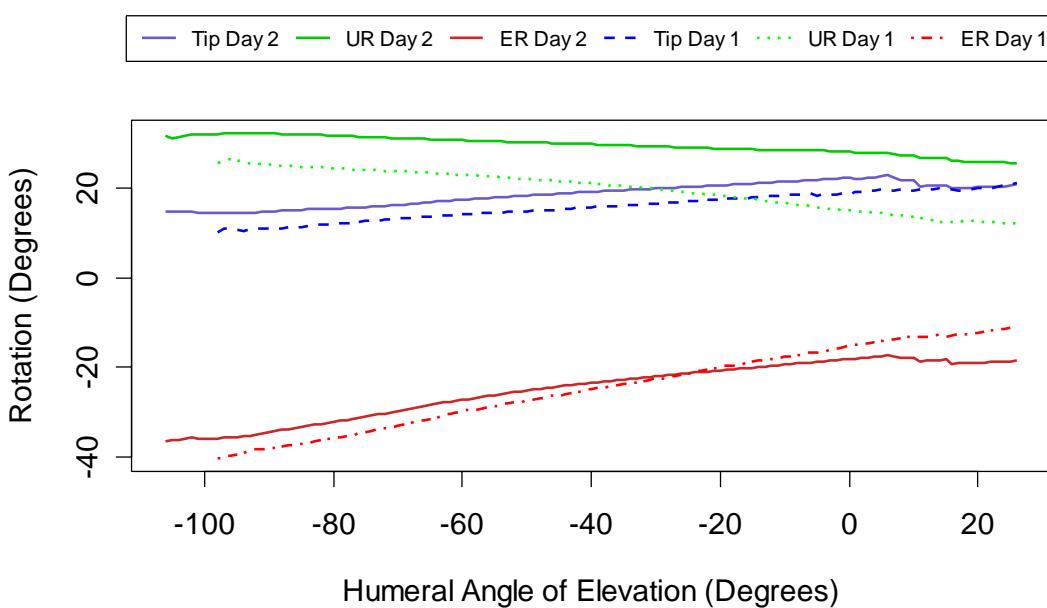
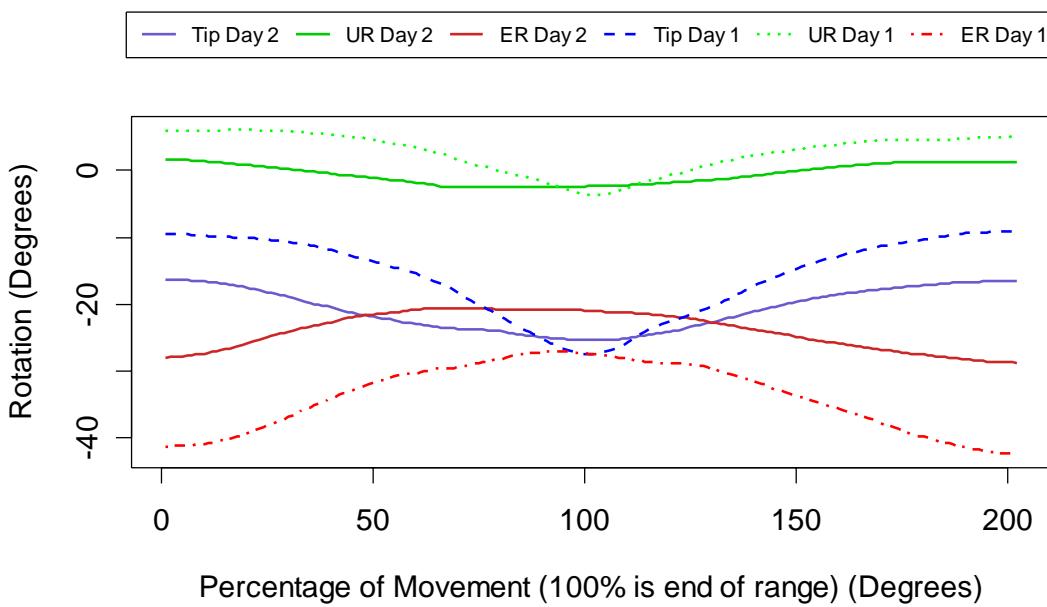
**Figure 5-18** Horizontal Adduction: ICC(3,10) throughout the range of angle of elevation.



**Figure 5-19** Abduction: Example of day 1 vs. day 2 (subject 7). Tip= posterior tipping, UR= upward rotation, ER= external rotation.



**Figure 5-20** Reaching: Example of day 1 vs. day 2 (subject 4). Tip= posterior tipping, UR= upward rotation, ER= external rotation.



## 5.4 Discussion

### 5.4.1 Effect of Pins

The main concern with choosing bone pins as a gold standard was that they are invasive and pierce the skin. This may tether the skin and change its movement with respect to the bone. Karduna et al. (Karduna *et al.*, 2001) used bone pins to validate a method of measuring scapular motion. To validate their use, they did a calculation based on beam theory to make sure that the skin would not bend the pins. When they put pins into a cadaver and then pulled on the skin, they found negligible errors. They did not test to see if the pins changed the movement of the skin. To minimize the effect of the pins on the skin we placed the pins on the lateral scapular spine, where there is less skin movement. We also performed a preliminary cadaver experiment to verify that skin movement was minimal (Chapter 2).

The rms differences comparing the patches with pins in and patches without the pins ( $1.1^\circ$ - $5.0^\circ$ ) were very similar in magnitude to the rms differences comparing movement of two different trials with the pins in ( $1.1^\circ$ - $4.7^\circ$ ). This is suggestive that the effect of the pins on the skin movement was small. The ICCs (0.7-0.99) were also high comparing patches with the pins to patches without the pins. Again, this suggests that the pins did not change skin motion substantially.

The combination of previous work by Karduna et al., (Karduna *et al.*, 2001), our previous cadaver work and the results of this study appear to validate the use of the bone pins as a gold standard.

### **5.4.2 Cross Correlation**

The cross correlation results showed that the patches captured the motion of the scapula. It does not signify the accuracy of the technique but does suggest that with the proper correction factor, the patches could accurately measure scapular motion. The highest correlations were found for horizontal adduction (0.95-0.99) while the worst correlations were for the hand behind back movement (0.68-0.87).

### **5.4.3 Accuracy**

Our original hypothesis was that different patches would be better for different movements. Based strictly on the means, patch 6 was the best patch for tipping, patch 4 for upward rotation and patch 1 for external rotation. Because of the limited numbers in our study statistical power was limited and thus it was difficult to determine exactly which patches were best for which movements. Patch 1 did tend to be the most accurate patch for external rotation. Patches 4 and 6 seemed to be the most accurate overall. Patch 6 was not as accurate as patch 1 for external rotation but was statistically the same as patch 4 for upward rotation. Patch 4 was statistically no different than the most accurate patch for all rotations. The least accurate patches overall were 3 and 5.

These results were not surprising. Patches 3 and 5 both included the most inferior markers but were missing the most superior markers, while patches 1 and 4 included the most superior markers but were missing the most inferior markers. Patch 6 included all of the markers. The inferior aspect of the scapula slides the most underneath the skin while the skin along the scapular spine exhibits much less sliding. Patch 1 was the most accurate for external rotation, probably due to its location along the spine of the scapula. It was not as

accurate for upward rotation and especially for posterior tipping. Choo found the same phenomenon with posterior tipping in his cadaver study (Choo, 2001). He thought that the spine of the scapula acted like a cylinder under the markers, thus when the scapula tipped the cylinder would rotate under the markers instead of tilting them with the scapula. Patches 4 and 6 included more markers over the infraspinous fossa and thus could compensate better for this error. Patches with large numbers of markers may be inherently better overall since errors in a couple of markers may be compensated for by the rest of the markers.

The results of the skin correction factor were impressive. RMS errors (for patch 4) in abduction were reduced from  $9.7^\circ$  in posterior tipping,  $7.5^\circ$  in upward rotation and  $9.5^\circ$  in external rotation to  $2.3^\circ$ ,  $2.8^\circ$ , and  $2.8^\circ$  respectively. The minimum improvement in error was from  $4.2^\circ$  to  $2.0^\circ$  for upward rotation during reaching. Inspection of individual graphs does show some movements where the correction factor actually increased the error. These tended to be rotations with relatively small overall motion and the error from the correction factor tended to be low.

The accuracy results compare very favourably to Karduna et al. (Karduna *et al.*, 2001). For corrected upward rotation their rms errors ranged from  $2.0\text{-}4.1^\circ$  with the acromial method and from  $4.0\text{-}4.5^\circ$  with the tracker method. They did not correct the other rotations. Posterior tilt errors ranged from  $3.7\text{-}8.6^\circ$  for the acromial method and  $3.2\text{-}6.8^\circ$  for the tracker method. Internal rotation errors ranged from  $6.2\text{-}11.4^\circ$  with the acromial method and  $3.2\text{-}5.0^\circ$  for the tracker method. In contrast, for our method, no rotation had an rms error greater than  $3.0^\circ$ . If Karduna et al. developed correction factors for all rotations their results may have come closer to ours.

The rms errors from this dynamic method are less than the statically determined changes in scapular position (Chapter 4), even though the static measurements are used in the skin correction factor. This is understandable since a total of seven different digitizations were used in the correction method of the dynamic measurement. Each individual digitization contributes to the correction factor when the humerus is within 100° of this position. Thus multiple reference frames are used for every position. This would have the effect of averaging the error over a number of measurements, thus decreasing the overall error.

The movements tested in the study were chosen to put the scapula through as great a range as possible as well as to test movements that may be more functional. They were also chosen to be slightly different from the work of Karduna et al.(Karduna *et al.*, 2001). As mentioned in Chapter 3 this allowed us to collect gold standard data from a wider range of movements, but it also allowed us to further validate skin based methods. The fact that very different skin based methods work over a wide variety of motions adds confidence that these methods really are testing scapular movement.

The correction factor that Karduna et al. (Karduna *et al.*, 2001) used was a linear model based on scapular angle. It was calculated by comparing the gold standard data to the markers using the combined data from all eight subjects. An advantage of our correction factor is that it was based entirely on non-invasive data and was customized for every subject. This may be a great advantage if shoulder pathology affects the relationship between the skin markers and the scapula during movement. Potentially this method may decrease the error associated with the initial digitization process by averaging measurements. The major disadvantage to this correction method is time. Digitization of landmarks adds considerable time to data collection. Holding the digitization positions may be difficult in

subjects with shoulder dysfunction. This effect can be minimized by decreasing the number of movements tested and/or decreasing the number of digitization positions. Changing the number of digitization positions would be particularly appropriate if a particular range of motion was of interest. There is no need to calibrate the skin error outside the range of interest.

Compared to other skin correction techniques (Lucchetti *et al.*, 1998; Schmidt *et al.*, 1999; Alexander and Andriacchi, 2001), this new technique is the only one to directly take into account movement of the skin with respect of the bone during the actual movements tested. Both Lucchetti *et al.* and Schmidt *et al.* measured skin movement during contrived movements (i.e. holding one joint still while moving the other joint) and then inferred what the skin movement was during more natural movements.

Another advantage of this skin correction factor is that it is not tied into the patch technique. It could easily be used with other techniques such as the acromial marker or the tracker. It is also not tied into any particular movement. It can easily be modified to suit custom movements.

#### **5.4.4 Reliability**

As with accuracy, reliability of the different patches is hard to analyze because of the small ( $n=7$ ) sample size. The only real statistical difference (for rms differences) was for external rotation where patch 1 was more reliable than patches 2, 3 or 5 and patch 4 was significantly more reliable than patches 3 and 5. Additional subjects would be able to improve the power but considering the small differences in means, it is questionable that any differences would be clinically significant.

An attempt was made to make this experiment somewhat similar to a clinical situation. The goal of a clinically feasible method to measure scapular motion will not be achieved if we use techniques that are too restrictive to use in the clinic. Optoelectronic markers were placed on the scapula using rough measurements based on anatomical landmarks. The position of the markers was not marked between days of testing to allow for more reliable retesting. This type of control would not be possible in a clinical situation.

Several previous studies have guided movement by providing a plane to guide arm movement or another object to follow (Finley and Lee, 2003; Borstad and Ludewig, 2002; Pascoal *et al.*, 2000; McQuade *et al.*, 1998). This is an artificial situation which the subject is unlikely to encounter in real life. Although it standardizes the movement it does not necessarily allow the subject to use a normal movement pattern.

It would not be surprising if the reliability in this study was less than that quoted in other studies. The rms differences in this study ranged from  $3.3^\circ$  to  $7.6^\circ$ . Ludewig and Cook (Ludewig *et al.*, 1996) found the day to day standard error of measurement to be  $2^\circ$  to  $4^\circ$ . RMS values are more conservative than the standard error of measurement so these values are very similar. They stopped scaption at  $120^\circ$  which also may help explain why our results are a little higher. Ludewig and Cook also looked at ICCs for same day movements. Their results ranged from 0.93 to 0.98 which is quite comparable to the ICCs calculated in this study between the patches with pins and the patches without pins which did not drop below 0.85 in abduction. The ICC model they used (2,1) generally gives more conservative results than the model we used (3,10). ICC(3,10) was used in this study because there was only one rater (D.B.), and the average of ten repetitions was used (Portney and Watkins, 2000; Shrout and Fleiss, 1979; Rankin and Stokes, 1998).

According to Portney and Watkins (Portney and Watkins, 2000), ICC values above 0.75 represent good reliability while those less than 0.75 represent poor to moderate reliability. Using these criteria, abduction demonstrated good reliability for both posterior tipping and upward rotation but more moderate reliability for external rotation. The reaching movement had good reliability for all rotations. Hand behind back demonstrated good reliability for posterior tipping but only moderate reliability for the other rotations. Finally, H.Add demonstrated good reliability for upward rotation throughout range. Posterior tipping reliability was only good for the first half of range of motion, while external rotation reliability was only good during the middle range.

#### **5.4.5 Conclusion and Recommendations**

When combined with the custom skin correction factor, the patch method of measuring dynamic scapular motion is both accurate and reliable. Overall, current results suggest it is more accurate than other non-invasive dynamic measures. The skin correction factor as described should be transferable to other measurement techniques. This measurement technique can now be used to compare shoulder movement in populations with shoulder pathology and healthy subjects. Once the differences between the populations are well known, we can then try to simplify the procedure so it can be used in clinical situations.

## **Chapter Six: General Conclusions**

The overall objective of this thesis was to validate a new skin based method of measuring scapular motion. A series of coordinated studies were needed to satisfy this goal. The first was to verify that it was valid to use bone pins as a gold standard. This was shown in a cadaver study in Chapter 2. The next step was to measure dynamic three-dimensional scapular motion in vivo using this gold standard (Chapter 3). The patient specific skin correction factor relied on the use of the digitization of bony landmarks. It was therefore necessary to determine the accuracy of this method (Chapter 4). The final step was to determine if the new skin-based marker method with the patient specific correction factor was an accurate and reliable measure of scapular motion (Chapter 5).

Humeral elevation, especially in the scapular plane, has become a standard movement in measuring scapular motion. As shown in Chapter 3, the more functional movements such as reaching and hand behind back tend to have more complex scapular movement. They also tend to be less reliable. When compared to scapular motion from other studies, it is apparent that the degree of scapular internal/external rotation is task dependent. While in pure flexion the scapula externally rotates, it internally rotates with a reaching movement. These points demonstrate the need to study more functional movements when assessing scapular motion.

This study has produced the first evidence that the digitization of bony landmarks is an accurate way of measuring change in scapular position. This helps validate studies which have used this method in the past.

The new skin marker based method with the subject specific skin correction factor has proven to be an accurate and reliable measure of three dimensional scapular motion. Either

different patches can be used for different rotations, or a single patch can be used for all rotations. Both of the patches which were accurate for all rotations consisted of several markers. The use of several markers rather than a patch of four may be able to correct for small local skin deformations by averaging them over the entire patch area. The subject specific skin correction factor is a unique method which directly measures the amount of skin movement compared to the bone. Because it calculates multiple sets of angles it is computationally intensive but it is also flexible and can be customized to different movements and likely to different body parts.

## **6.1 Future Research**

Both the accuracy and reliability of this method of measuring scapular motion are very good and it is ready to be used to analyze scapular movement. Overall, it is more accurate than other non-invasive techniques (Karduna *et al.*, 2001). Although this technique is ready for use, there is room for improvement. Changes to the skin correction factor may be possible which would further improve the accuracy of this technique. Additional improvements can be made to take advantage of the increased accuracy of this study. The current recommendations for the axis system may have little relation to shoulder pathology and simple modelling may allow a better understanding of the forces experienced by the glenohumeral joint.

The skin correction factor has not been optimized. The initial parameters chosen worked very well from the start. Possible improvements could be made on how one reference frame is transitioned to another. The current model gradually and linearly fades a reference frame out over 100°. A non linear model or differences in the length of phase out may work better.

The digitization method itself is not completely accurate. A large mistake in digitization may have a large effect on a portion of the curve. These errors could be noticeable as blips in the curve. The uncorrected curve is generally correct in waveform but not in magnitude. It is theoretically possible to use it to identify and help remove “blips.” Improvements to make the digitization process more accurate would also help with the skin correction factor.

Understanding how scapular movement affects glenohumeral joint stresses is an important part of the puzzle to link scapular movement to glenohumeral pathology. To make this link, a number of steps should be followed. First, the orientation of the glenoid fossa with respect to our defined axis systems needs to be determined. Ideally we should change our axis system to correspond to the orientation of the glenoid fossa rather than arbitrary bony landmarks. An MRI study comparing the position of the digitized landmarks to the glenoid fossa would determine this relationship. Second, movement of the humerus should be reported with respect to the scapula and not the humerus with respect to the thorax and the scapula with respect to the thorax. This would help with direct visualization of the relationship between the humerus and the scapula instead of trying to understand this relationship from a combination of scapulothoracic and humerothoracic angles. Third, a simplified model of the glenohumeral joint should be produced to allow for an inverse dynamics analysis and calculation of some of the forces the glenohumeral ligaments and rotator cuff muscles need to endure. The combination of the above three points would take advantage of the increased accuracy of this technique and progress our knowledge of shoulder pathology.

A particular point of interest for future studies is the hysteresis between concentric and eccentric phases of humeral elevation. I hypothesize that this hysteresis is what we see

clinically as scapular winging and abnormal scapular movement. I further hypothesize that the purpose of this hysteresis is to reduce the load on the rotator cuff during the eccentric phase.

Ideally, once we better understand how scapular motion contributes to glenohumeral pathology, a clinically useful method can be developed to assess scapular motion. Such a method could be used as both an assessment tool as well as an outcome measure for rehabilitation protocols.

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## Appendix A Subject Data

**Table A-1** Age, height, weight and body mass index of the subjects.

Subject	Age	Height	Weight	BMI
1	29	161	57	22.0
2	27	173	65	21.7
3	33	177	88	28.1
4	34	161	77	29.7
5	36	178	80	25.2
6	25	183	94	28.1
7	24	171	50	17.1
Average	29.7	172.0	73.0	24.6
Standard Deviation	4.7	8.4	16.2	4.5

**Table A-2** Tricep and subscapular skinfold of the subjects.

Subject	Tricep Skinfold (mm)				Subscapular Skinfold (mm)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
1	12.0	9.5	10.5	10.7	10.5	10.5	10.5	10.5
2	4.5	4.0	4.0	4.2	10.5	9.5	10.5	10.2
3	16.0	18.0	18.0	17.3	19.0	20.0	22.0	20.3
4	22.0	24.0	24.0	23.3	33.0	33.0	34.0	33.3
5	14.0	13.0	14.5	13.8	16.5	14.5	14.5	15.2
6	24.5	24.5	25.5	24.8	17.0	18.0	16.5	17.2
7	15.0	15.0	16.0	15.3	11.0	12.0	10.5	11.2
Average	15.6				16.8			
Standard Deviation	7.1				8.2			

## Appendix B Statistical Analysis

NS: not significant

S: significant

### B.1 Digitization of Bony Landmarks

#### B.1.1 Absolute Mean Error Analysis

**Table B-1** Comparison of absolute mean errors for posterior tipping by repeated measures ANOVA.

<b>Summary of all Effects; design: (cal_data_av_nrms2.sta)</b>						
1-POSITION						
Effect	df	MS	df	MS	F	p-level
	Effect	Error	Error	15.82464		0.427721 (NS)
1	11	16.36014	66	1.03384		

**Table B-2** Comparison of absolute mean errors for upward rotation by repeated measures ANOVA.

<b>Univariate Test with Adjusted Degrees of Freedom</b>					
$F = 7.855361$					
MAIN EFFECT: POSITION					
		Greenhs.	Huynh	Lower	
	Unadjstd	Geisser	Feldt	Bound	
Epsilon		0.285323	0.634447	0.090909	
df 1	11	3.138548	6.978915		1
df 2	66	18.83129	41.87349		6
p-level	1.63E-08	0.001201	4.7E-06 (S)	0.031052	

**Table B-3** Tukey's HSD posthoc results for absolute mean errors in upward rotation.

Tukey HSD test; variable Var.1 (cal_data_av_nrms2.sta)														
Probabilities for Post Hoc Tests														
MAIN EFFECT: POSITION														
	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}		
	.3153310	-4.10206	-5.75622	2.031436	.8819578	-.884360	.1496617	-.303561	-1.30322	-2.49486	-1.50162	-3.58204		
1 {1}		0.012178	0.000185	0.933519	0.999997	0.995662		1	0.999993	0.955103	0.378179	0.904711	0.045707	
2 {2}	0.012178		0.947904	0.000172	0.002533	0.193811	0.018869	0.057645	0.384347	0.957252	0.49847	0.999999		
3 {3}	0.000185	0.947904		0.00012	0.000128	0.003472	0.000242	0.000677	0.011068	0.178698	0.018724	0.749477		
4 {4}	0.933519	0.000172	0.00012		0.997007	0.323234	0.882582	0.658429	0.155332	0.009063	0.103798	0.000457		
5 {5}	0.999997	0.002533	0.000128	0.997007		0.920034	0.999959	0.996081	0.743557	0.142993	0.62951	0.010744		
6 {6}	0.995662	0.193811	0.003472	0.323234	0.920034		0.998853	0.999996		1	0.95664	0.999993	0.44126	
7 {7}		1	0.018869	0.000242	0.882582	0.999959	0.998853		1	0.97948	0.472289	0.948515	0.067182	
8 {8}	0.999993	0.057645	0.000677	0.658429	0.996081	0.999996		1	0.999177	0.740244	0.995712	0.173021		
9 {9}	0.955103	0.384347	0.011068	0.155332	0.743557		1	0.97948	0.999177		0.995904		1	0.691205
10 {10}	0.378179	0.957252	0.178698	0.009063	0.142993	0.95664	0.472289	0.740244	0.995904		0.999224	0.998198		
11 {11}	0.904711	0.49847	0.018724	0.103798	0.62951	0.999993	0.948515	0.995712		1	0.999224		0.797572	
12 {12}	0.045707	0.999999	0.749477	0.000457	0.010744	0.44126	0.067182	0.173021	0.691205	0.998198	0.797572			

**Table B-4** Comparison of absolute mean errors for external rotation by repeated measures ANOVA.

<b>Univariate Test with Adjusted Degrees of Freedom</b>				
F = 2.656229				
MAIN EFFECT: POSITION				
	Greenhs.	Huynh	Lower	
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.19366	0.303327	0.090909
df 1	11	2.130256	3.336601	1
df 2	66	12.78154	20.01961	6
p-level	0.007035	0.106164	0.071294 (NS)	0.154267

### B.1.2 RMS Error Analysis

**Table B-5** Comparison of RMS errors for posterior tipping by repeated measures ANOVA.

<b>Univariate Test with Adjusted Degrees of Freedom</b>				
F = 4.515554				
MAIN EFFECT: POSTITIO				
	Greenhs.	Huynh	Lower	
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.222124	0.386052	0.090909
df 1	11	2.443361	4.246573	1
df 2	66	14.66017	25.47944	6
p-level	4.53E-05	0.024286	0.006083 (S)	0.077746

**Table B-6** Tukey's HSD posthoc results for rms errors in posterior tipping.

Tukey HSD test; variable Var.1 (cal_data_av4.sta)												
Probabilities for Post Hoc Tests												
MAIN EFFECT: POSTITIO												
	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}
	3.229247	5.093737	11.20140	2.580568	3.375446	3.618098	4.426024	3.699039	4.104383	4.607053	4.461431	2.905528
1 {1}		0.983214	0.00019	0.999999	1	1	0.999664	1	0.999985	0.998729	0.999557	1
2 {2}	0.983214		0.006703	0.872985	0.991246	0.997629	0.999999	0.998581	0.999947	1	0.999999	0.946454
3 {3}	0.00019	0.006703		0.000131	0.000229	0.000321	0.00162	0.000382	0.000805	0.002387	0.001745	0.000149
4 {4}	0.999999	0.872985	0.000131		0.999994	0.999916	0.984497	0.999825	0.996837	0.968696	0.982046	1
5 {5}	1	0.991246	0.000229	0.999994		1	0.999905	1	0.999998	0.999559	0.999868	1
6 {6}	1	0.997629	0.000321	0.999916	1		0.999993	1	1	0.999948	0.99999	0.999998
7 {7}	0.999664	0.999999	0.00162	0.984497	0.999905	0.999993		0.999998	1	1	1	0.996897
8 {8}	1	0.998581	0.000382	0.999825	1	1	0.999998		1	0.999978	0.999996	0.999994
9 {9}	0.999985	0.999947	0.000805	0.996837	0.999998	1	1	1		1	1	0.999659
10 {10}	0.998729	1	0.002387	0.968696	0.999559	0.999948	1	0.999978	1		1	0.991928
11 {11}	0.999557	0.999999	0.001745	0.982046	0.999868	0.99999	1	0.999996	1	1		0.996208
12 {12}	1	0.946454	0.000149	1	1	0.999998	0.996897	0.999994	0.999659	0.991928	0.996208	

**Table B-7** Comparison of RMS errors for upward rotation by repeated measures ANOVA

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**Summary of all Effects; design: (cal\_data\_av4.sta)**

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1-POSITION

df Effect	MS Effect	df Error	MS Error	F	p-level
1	11	14.02734	66	2.347139	5.976355 1.16E-06 (S)

**Table B-8** Comparison of RMS errors for external rotation by repeated measures ANOVA

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**Univariate Test with Adjusted Degrees of Freedom**

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F = 4.467164

MAIN EFFECT: POSITION

Epsilon	Greenhs.		Huynh	Lower
	Unadjstd	Geisser	Feldt	Bound
		0.245372	0.465261	0.090909
df 1	11	2.69909	5.11787	1
df 2	66	16.19454	30.70722	6
p-level	5.14E-05	0.0206	0.003377 (S)	0.078983

**Table B-9** Tukey's HSD posthoc results for rms errors in upward rotation.

Tukey HSD test; variable Var.1 (cal_data_av4.sta)														
Probabilities for Post Hoc Tests														
MAIN EFFECT: POSITION														
	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}		
	2.843103	4.393196	6.950289	2.871894	2.138365	1.578382	2.612225	2.482271	2.637376	4.254143	3.136283	3.849260		
1 {1}		0.759188	0.000368		1	0.999314	0.922104		1	0.999999		1	0.851069	
2 {2}	0.759188		0.098765	0.77992	0.224508	0.043834	0.573035	0.46449	0.59425		1	0.925107	0.999943	
3 {3}	0.000368	0.098765		0.0004	0.000127	0.00012	0.000195	0.000159	0.00021	0.064467	0.001006	0.01607		
4 {4}		1	0.77992	0.0004		0.998986	0.910317		1	0.999998		1	0.867238	
5 {5}	0.999314	0.224508	0.000127	0.998986		0.999924	0.999986		1	0.999976	0.309987	0.985576	0.631917	
6 {6}	0.922104	0.043834	0.00012	0.910317	0.999924		0.981035	0.99354	0.977256	0.068746	0.753433	0.215788		
7 {7}		1	0.573035	0.000195		1	0.999986	0.981035		1	1	0.688437	0.999961	0.932405
8 {8}	0.999999	0.46449	0.000159	0.999998		1	0.99354		1		1	0.580715	0.99966	0.875378
9 {9}		1	0.59425	0.00021		1	0.999976	0.977256		1		0.708429	0.999976	0.940923
10 {10}	0.851069		1	0.064467	0.867238	0.309987	0.068746	0.688437	0.580715	0.708429		0.966185	0.999997	
11 {11}		1	0.925107	0.001006		1	0.985576	0.753433	0.999961	0.99966	0.999976	0.966185		0.999236
12 {12}	0.984613	0.999943	0.01607	0.987766	0.631917	0.215788	0.932405	0.875378	0.940923	0.999997	0.999236			

**Table B-10** Tukey's HSD posthoc results for rms errors in external rotation.

Tukey HSD test; variable Var.1 (cal_data_av4.sta)														
Probabilities for Post Hoc Tests														
MAIN EFFECT: POSITION														
	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}		
	2.353514	5.031842	10.13167	2.510742	2.199172	3.394445	2.788155	3.788492	4.420789	3.564130	1.993158	6.649738		
1 {1}		0.855873	0.000406		1	1	0.999942		1	0.998735	0.973202	0.999747	1	0.22718
2 {2}	0.855873		0.069812	0.898387	0.805848	0.995874	0.952012	0.999674		1	0.99845	0.728152	0.996277	
3 {3}	0.000406	0.069812		0.000529	0.000307	0.003144	0.000891	0.006998	0.023899	0.004442	0.000233	0.537126		
4 {4}		1	0.898387	0.000529		1	0.999989		1	0.999577	0.985303	0.999935	1	0.276067
5 {5}		1	0.805848	0.000307		1	0.999776		1	0.996813	0.955167	0.999217	1	0.185366
6 {6}	0.999942	0.995874	0.003144	0.999989	0.999776				1	1	0.99995		1	0.636955
7 {7}		1	0.952012	0.000891		1	1	1		0.999961	0.995975	0.999997	0.999996	0.376785
8 {8}	0.998735	0.999674	0.006998	0.999577	0.996813		1	0.999961		1	1	0.991054	0.795761	
9 {9}	0.973202		1	0.023899	0.985303	0.955167	0.99995	0.995975		1		0.999992	0.919474	0.954137
10 {10}	0.999747	0.99845	0.004442	0.999935	0.999217		1	0.999997		1	0.999992		0.997123	0.70905
11 {11}		1	0.728152	0.000233		1	1	0.998981	0.999996	0.991054	0.919474	0.997123		0.138786
12 {12}	0.22718	0.996277	0.537126	0.276067	0.185366	0.636955	0.376785	0.795761	0.954137	0.70905	0.138786			

## B.2 Accuracy and Reliability of New Skin Based Method

### B.2.1 RMS Error Analysis

**Table B-11** Comparison of RMS errors for posterior tipping by repeated measures ANOVA

<b>Summary of all Effects; design: (rms_acc_tip.sta)</b>						
1-MOVEMENT, 2-PATCHES						
	df Effect	MS Effect	df Error	MS Error	F	p-level
1	3	19.13077	18	2.801666	6.828355	0.00287
2	5	3.286637	30	0.300084	10.95238	4.61E-06
12	15	2.34986	90	0.329112	7.139993	5.12E-10

**Table B-12** Comparison of RMS errors for posterior tipping by repeated measures ANOVA: Huynh Feldt adjustment for main effect of patch.

<b>Univariate Test with Adjusted Degrees of Freedom</b>				
F = 10.95238				
MAIN EFFECT: PATCHES				
	Greenhs. Unadjstd	Huynh Geisser	Feldt	Lower Bound
Epsilon		0.30447	0.386652	0.2
df 1	5	1.522351	1.933259	1
df 2	30	9.134105	11.59955	6
p-level	4.61E-06	0.00533	0.002258 (S)	0.016216

**Table B-13** Tukey's HSD posthoc results for rms errors for main effect of patch for posterior tipping.

<b>Tukey HSD test; variable Var.1 (rms_acc_tip.sta)</b>							
Probabilities for Post Hoc Tests							
MAIN EFFECT: PATCHES							
	{1}	{2}	{3}	{4}	{5}	{6}	
	2.701875	2.030211	2.639003	2.148536	2.049412	1.885456	
....	1 {1}	0.001075	0.99801	0.008385	0.001482	0.000191	
....	2 {2}	0.001075		0.003174	0.963823	0.999994	0.918008
....	3 {3}	0.99801	0.003174		0.024349	0.004444	0.000324
....	4 {4}	0.008385	0.963823	0.024349		0.983236	0.482781
....	5 {5}	0.001482	0.999994	0.004444	0.983236		0.869332
....	6 {6}	0.000191	0.918008	0.000324	0.482781	0.869332	

**Table B-14** Comparison of RMS errors for posterior tipping by repeated measures ANOVA: Huynh Feldt adustment for main effect of movement.

<b>Univariate Test with Adjusted Degrees of Freedom</b>				
$F = 6.828355$				
MAIN EFFECT: MOVEMENT				
	Greenhs.	Huynh	Lower	
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.548383	0.728386	0.333333
df 1	3	1.645149	2.185159	1
df 2	18	9.870894	13.11096	6
p-level	0.00287	0.016732	0.008215 (S)	0.039953

**Table B-15** Tukey's HSD posthoc results for rms errors for main effect of movement for posterior tipping.

<b>Tukey HSD test; variable Var.1 (rms_acc_tip.sta)</b>						
Probabilities for Post Hoc Tests						
MAIN EFFECT: MOVEMENT						
		{1}	{2}	{3}	{4}	
		2.538422	2.255966	2.872101	1.303173	
1	.... {1}		0.865516	0.798027	<b>0.016057</b>	
2	.... {2}	0.865516		0.35894	0.076554	
3	.... {3}	0.798027	0.35894		<b>0.002366</b>	
4	.... {4}	<b>0.016057</b>	0.076554	<b>0.002366</b>		

**Table B-16** Simple main effects for reaching and posterior tipping. ANOVA and Tukey's HSD posthoc.

<b>Summary of all Effects; design: (rms_acc_tip_mov1.sta)</b>						
1-PATCH						
	df	MS	df	MS	F	p-level
	Effect	Effect	Error	Error		
1	5	2.684293	30	0.477758	5.618517	0.000905 (S)
Tukey HSD test; variable Var.1 (rms_acc_tip_mov1.sta)						
Probabilities for Post Hoc Tests						
MAIN EFFECT: PATCH						
	{1}	{2}	{3}	{4}	{5}	{6}
	3.364511	1.936122	1.939198	2.574827	1.671507	2.049634
1 {1}		<b>0.006722</b>	<b>0.006866</b>	0.29629	<b>0.001089</b>	<b>0.014627</b>
2 {2}	<b>0.006722</b>			1 0.524575	0.978501	0.999621
3 {3}	<b>0.006866</b>		1	0.529732	0.977388	0.999669
4 {4}	0.29629	0.524575	0.529732		0.173401	0.714138
5 {5}	<b>0.001089</b>	0.978501	0.977388	0.173401		0.906394
6 {6}	<b>0.014627</b>	0.999621	0.999669	0.714138	0.906394	

**Table B-17** Simple main effects for hand behind back and posterior tipping. ANOVA and Tukey's HSD posthoc.

<b>Summary of all Effects; design: (rms_acc_tip_mov1.sta)</b>						
1-PATCH						
	df Effect	MS Effect	df Error	MS Error	F	p-level
1	5	6.915242	30	0.369268	18.72689	1.99E-08
Tukey HSD test; variable Var.1 (rms_acc_tip_mov1.sta)						
Probabilities for Post Hoc Tests						
MAIN EFFECT: PATCH						
	{1}	{2}	{3}	{4}	{5}	{6}
	3.074786	2.201540	4.709008	2.277174	2.943817	2.026278
1 {1}		0.10751	0.000398	0.169981	0.998534	0.032557
2 {2}	0.10751		0.000134	0.999903	0.23143	0.994077
3 {3}	0.000398	0.000134		0.000134	0.000219	0.000134
4 {4}	0.169981	0.999903	0.000134		0.3384	0.970159
5 {5}	0.998534	0.23143	0.000219	0.3384		0.080757
6 {6}	0.032557	0.994077	0.000134	0.970159	0.080757	

**Table B-18** Simple main effects for horizontal adduction and posterior tipping. ANOVA and Tukey's HSD posthoc.

---

**Summary of all Effects; design: (rms\_acc\_tip\_mov1.sta)**

---

1-PATCH

	df	MS	df	MS	F	p-level
	Effect	Effect	Error	Error		
1	5	0.255412	30	0.098476	2.593645	0.045911 (S)

Tukey HSD test; variable Var.1 (rms\_acc\_tip\_mov1.sta)

Probabilities for Post Hoc Tests

MAIN EFFECT: PATCH

	{1}	{2}	{3}	{4}	{5}	{6}
	1.506344	1.520247	1.036457	1.352130	1.200659	1.203200
1 {1}		0.999999	0.084945	0.938451	0.467428	0.476542
2 {2}	0.999999		0.071038	0.913591	0.418744	0.42748
3 {3}	0.084945	0.071038		0.432237	0.921122	0.916282
4 {4}	0.938451	0.913591	0.432237		0.942751	0.946554
5 {5}	0.467428	0.418744	0.921122	0.942751		1
6 {6}	0.476542	0.42748	0.916282	0.946554		1

**Table B-19** Comparison of RMS errors for upward rotation by repeated measures ANOVA

---

**Summary of all Effects; design: (rms\_acc\_ur.sta)**

---

1-MOVEMENT, 2-PATCHES

Effect	df	MS	df	MS	F	p-level
	Effect	Error	Error	Error		
1	3	9.427083	18	4.025103	2.342072	0.107383 (NS)
2	5	0.957804	30	0.244829	3.912141	0.00754 (S)
12	15	0.187411	90	0.115163	1.627357	0.081953 (NS)

---

**Table B-20** Comparison of RMS errors for upward rotation by repeated measures ANOVA: Huynh Feldt adustment for main effect of patch.

---

**Univariate Test with Adjusted Degrees of Freedom**

---

F = 3.912141

MAIN EFFECT: PATCHES

	Greenhs.		Huynh	Lower
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.337416	0.454892	0.2
df 1	5	1.68708	2.27446	1
df 2	30	10.12248	13.64676	6
p-level	0.00754	0.060398	0.041164 (S)	0.095299

---

**Table B-21** Tukey's HSD posthoc results for rms errors for main effect of patch for upward rotation.

<b>Tukey HSD test; variable Var.1 (rms_acc_ur.sta)</b>							
Probabilities for Post Hoc Tests							
MAIN EFFECT: PATCHES							
		{1}	{2}	{3}	{4}	{5}	{6}
		2.184984	2.034160	2.472397	1.959883	2.201711	2.033095
....	1	{1}	0.860501	0.279495	0.541046	0.999995	0.856977
....	2	{2}	0.860501	0.026558	0.992835	0.800104	1
....	3	{3}	0.279495	0.026558	0.006561	0.341217	0.026046
....	4	{4}	0.541046	0.992835	0.006561	0.463663	0.993296
....	5	{5}	0.999995	0.800104	0.341217	0.463663	0.795921
....	6	{6}	0.856977	1	0.026046	0.993296	0.795921

**Table B-22** Comparison of RMS errors for external rotation by repeated measures ANOVA

<b>Summary of all Effects; design: (rms_acc_er.sta)</b>						
1-MOVEMENT, 2-PATCHES						
	df	MS	df	MS	F	p-level
	Effect	Effect	Error	Error		
1	3	6.606888	18	2.419988	2.730133	0.074234 (NS)
2	5	13.90281	30	0.181546	76.58007	3.68E-16 (S)
12	15	0.856237	90	0.282237	3.033752	0.000566 (NS)

**Table B-23** Comparison of RMS errors for external rotation by repeated measures ANOVA: Huynh Feldt adustment for main effect of patch.

<b>Univariate Test with Adjusted Degrees of Freedom</b>				
F = 76.58007				
MAIN EFFECT: PATCHES				
	Greenhs.	Huynh	Lower	
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.363543	0.512829	0.2
df 1	5	1.817713	2.564144	1
df 2	30	10.90628	15.38487	6
p-level	3.68E-16	4.97E-07	3.45E-09 (S)	0.000123

**Table B-24** Tukey's HSD posthoc results for rms errors for main effect of patch for external rotation.

<b>Tukey HSD test; variable Var.1 (rms_acc_er.sta)</b>							
Probabilities for Post Hoc Tests							
MAIN EFFECT: PATCHES							
	{1}	{2}	{3}	{4}	{5}	{6}	
	1.862257	2.579353	3.825160	2.144480	3.018394	2.354925	
....	1 {1}	0.00014	0.000134	0.162823	0.000134	0.002057	
....	2 {2}	0.00014	0.000134	0.007588	0.006907	0.381911	
....	3 {3}	0.000134	0.000134	0.000134	0.000135	0.000134	
....	4 {4}	0.162823	0.007588	0.000134	0.000134	0.452147	
....	5 {5}	0.000134	0.006907	0.000135	0.000134		0.000165
....	6 {6}	0.002057	0.381911	0.000134	0.452147	0.000165	

## B.2.2 RMS Difference Analysis

**Table B-25** Comparison of RMS differences for posterior tipping by repeated measures ANOVA

---

### Summary of all Effects; design: (rms\_rel\_tip.sta)

---

1-MOVEMENT, 2-PATCHES

Effect	df	MS	df	MS	F	p-level
	Effect	Error	Error	Error		
1	3	31.04209	18	19.44831	1.596134	0.225235 (NS)
2	5	3.533216	30	0.869602	4.063026	0.006188 (S)
12	15	3.505781	90	0.697467	5.026447	4.62E-07 (S)

**Table B-26** Comparison of RMS differences for posterior tipping by repeated measures ANOVA: Huynh Feldt adustment for main effect of patch.

---

### Univariate Test with Adjusted Degrees of Freedom

---

F = 4.063026

MAIN EFFECT: PATCHES

	Greenhs.		Huynh	Lower
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.290319	0.358859	0.2
df 1	5	1.451596	1.794294	1
df 2	30	8.709578	10.76576	6
p-level	0.006188	0.065803	0.051801 (NS)	0.090438

**Table B-27** Tukey's HSD posthoc results for rms differences for main effect of patch for posterior tipping.

<b>Tukey HSD test; variable Var.1 (rms_rel_tip.sta)</b>							
Probabilities for Post Hoc Tests							
MAIN EFFECT: PATCHES							
		{1}	{2}	{3}	{4}	{5}	{6}
		3.991030	4.180843	4.806222	3.827757	4.346015	3.952990
....	1	{1}	0.971911	0.029422	0.985539	0.712465	0.999988
....	2	{2}	0.971911	0.153489	0.716955	0.984772	0.93982
....	3	{3}	0.029422	0.153489	0.005768	0.45304	0.020385
....	4	{4}	0.985539	0.716955	0.005768	0.324619	0.995749
....	5	{5}	0.712465	0.984772	0.45304	0.324619	0.619305
....	6	{6}	0.999988	0.93982	0.020385	0.995749	0.619305

**Table B-28** Comparison of RMS differences for upward rotation by repeated measures ANOVA

<b>Summary of all Effects; design: (rms_rel_ur.sta)</b>						
1-MOVEMENT, 2-PATCHES						
	df	MS	df	MS	F	p-level
Effect	Effect	Error	Error			
1	3	39.76678	18	42.81234	0.928863	0.44701 (NS)
2	5	0.618616	30	0.428384	1.44407	0.237409 (NS)
12	15	0.08224	90	0.152002	0.541046	0.910345 (NS)

**Table B-29** Comparison of RMS differences for external rotation by repeated measures ANOVA

---

**Summary of all Effects; design: (rms\_rel\_er.sta)**

---

1-MOVEMENT, 2-PATCHES

Effect	df	MS	df	MS	F	p-level
	Effect	Error	Error	Error		
1	3	16.26937	18	61.71147	0.263636	0.850671 (NS)
2	5	4.21405	30	0.32118	13.12054	8.23E-07 (S)
12	15	0.837598	90	0.361548	2.316696	0.007717 (S)

**Table B-30** Comparison of RMS differences for external rotation by repeated measures ANOVA: Huynh Feldt adustment for main effect of patch.

---

**Univariate Test with Adjusted Degrees of Freedom**

---

F = 13.12054

MAIN EFFECT: PATCHES

	Greenhs.		Huynh	Lower
	Unadjstd	Geisser	Feldt	Bound
Epsilon		0.418452	0.647218	0.2
df 1	5	2.092259	3.236092	1
df 2	30	12.55355	19.41655	6
p-level	8.23E-07	0.000765	5.05E-05 (S)	0.011068

**Table B-31** Tukey's HSD posthoc results for rms differences for main effect of patch for external rotation.

Tukey HSD test; variable Var.1 (rms_rel_er.sta)						
Probabilities for Post Hoc Tests						
MAIN EFFECT: PATCHES						
	{1}	{2}	{3}	{4}	{5}	{6}
	5.469057	6.002851	6.593616	5.742987	6.205347	5.893031
....	1 {1}	0.015933	0.000134	0.475758	0.000576	0.085332
....	2 {2}	0.015933	0.006159	0.53267	0.762598	0.977318
....	3 {3}	0.000134	0.006159	0.000186	0.138162	0.000983
....	4 {4}	0.475758	0.53267	0.000186	0.048855	0.917397
....	5 {5}	0.000576	0.762598	0.138162	0.048855	0.333474
....	6 {6}	0.085332	0.977318	0.000983	0.917397	0.333474

## **Appendix C Matlab Code**

This Appendix contains the matlab code used to compute the transformation matrices, Euler angles, skin correction factor and normalized data from the raw three-dimensional coordinates of the optoelectronic markers.

Config\_sub2p.m is a general configuration file for each subject. It determines specifics such as the number of files, which scapula, patch definitions marker locations etc. It calls on scapcalcpre.m to load in files and do preliminary calculations. It then calls on scapcalc.m which calculates all of the transformation matrices along with scapcalc2.m. Scapcalc.m calls anglecalc2.m which calculates the Euler angles. Scapcalc.m then calls export to save the data files.

Skincor\_all\_m.m loads in the data files from above and calculates the corrected angles for the patches. Once the angles are corrected the data can be normalized. Norms\_h\_cor.m and normconfig4.m normalize the data to humeral range.

Several utilities from other authors were used in these scripts. Soder.m which performs singular value decomposition to calculate the transformation matrices, was modified from Christoph Reinschmidt's code. Rxyzsolv.m and ryzxsolv.m which calculate the Euler angles for the scapula were also taken from Christoph Reinschmidt's code (rxyzsolv.m was modified by Anthony Choo to use atan2). Mkt.m which calculates the anatomical transformation matrix, was modified from Anthony Choo's code. ICCReliability.m which calculates the ICC, was taken from Patrick McCrea's code. T2x.m which calculates the ZXZ Euler angle sequence for the humerus was taken from Giampiero Campa's code.

### C.1 Config\_sub2p.m

```
% configuration file for matlab script  
% this is for the first trials with pins in sub2  
% sub2 will be without pins  
clear all;  
close all;  
  
movfile= 'movfile_sub2p';  
% left scapula = 0 right scapula = 1  
  
scap_side = 0;  
  
% number of files to process  
numfiles= 36;  
numfiles2 = 99 ;  
  
% file rootname  
rootname= 'sub2p';  
  
% file extension  
extension = '.dat';  
  
% digitize file  
digfile= 'sub2pt1';  
  
% number of movements tested  
nummove= 4;  
nummove2= 8;  
  
% index of humerus markers
```

```

humind = [ 14:37];

% start of skincor files
skincor_start= 3;

% num skincor files per movement
%skincor_num = 6;
skincor_num2= [8 6 6 6 ];

% where the skincor markers should be placed
skincor_mark_start= 80;
skincor_mark_num= 9;

% the start of the probe markers
startdig = 92;
% humeral head dig: the conical movement file
humhead = 2;

% start of movement files before and after cutting down the files
movestart= 81;
movestart2= 29;

% numscap markers
numscapmarkers= 14;
startscap=38;

% patches
patch{1} =[ 1:3 4:6 7:9 10:12] +startscap -1;
patch{2} =[ 7:9 10:12 13:15 16:18] +startscap -1;
patch{3} =[ 13:15 16:18 19:21 22:24]+startscap -1;
patch{4} =[ 1:3 4:6 7:9 10:12 13:15 16:18]+startscap -1;

```

```

patch{5} =[ 7:9 10:12 13:15 16:18 19:21 22:24]+startscap -1;
patch{6} =[ 1:3 4:6 7:9 10:12 13:15 16:18 19:21 22:24]+startscap -1;

patch{7} =[ 31:33 34:36 37:39 40:42 ] +startscap -1;
% number of patches
numpatch=7;

patchm = ones(numpatch,1);

% patch markers

%patchm(:,1:3) =[ (startscap + ( 3.*patch(:,1)-3)) (startscap + (3.*patch(:,1) -3)+1) (startscap
+ ( 3.*patch(:,1) -3) +2)];
%patchm(:,4:6) =[ (startscap + ( 3.*patch(:,2)-3)) (startscap + (3.*patch(:,2) -3)+1) (startscap
+ ( 3.*patch(:,2) -3) +2)];
%patchm(:,7:9) =[ (startscap + ( 3.*patch(:,3)-3)) (startscap + (3.*patch(:,3) -3)+1) (startscap
+ ( 3.*patch(:,3) -3) +2)];
%patchm(:,10:12) =[ (startscap + ( 3.*patch(:,4)-3)) (startscap + (3.*patch(:,4) -3)+1)
(startscap + ( 3.*patch(:,4) -3) +2)];

scapcalcpre;

custyes=0
refframe= { 'kin1'; 'kin1'; 'kin1'; 'kin1'; 'kin1'; 'kin1' ; 'kin1' ;'kin1'; 'kin1'};

scapcalc;

% recalculate for additional reference frames
cd ref1;

```

```

custyes=1;
refframe= { 'kin3' ; 'kin3' ; 'kin3'; 'kin3'; 'kin3'; 'kin3'; 'kin3'; 'kin3' };
scapcalc;
cd ..;

cd ref2;
refframe= { 'kin4' ; 'kin11' ; 'kin17'; 'kin23'; 'kin4'; 'kin11'; 'kin17'; 'kin23' };
scapcalc;
cd ..;

cd ref3;
refframe= { 'kin5' ; 'kin12' ; 'kin18'; 'kin24'; 'kin5'; 'kin12'; 'kin18'; 'kin24' };
scapcalc;
cd ..;

cd ref4;
refframe= { 'kin6' ; 'kin13' ; 'kin19'; 'kin25'; 'kin6'; 'kin13'; 'kin19'; 'kin25' };
scapcalc;
cd ..;

cd ref5;
refframe= { 'kin7' ; 'kin14' ; 'kin20'; 'kin26'; 'kin7'; 'kin14'; 'kin20'; 'kin26' };
scapcalc;
cd ..;

cd ref6;
refframe= { 'kin8' ; 'kin15' ; 'kin21'; 'kin27'; 'kin8'; 'kin15'; 'kin21'; 'kin27' };
scapcalc;
cd ..;

cd ref7;

```

```

refframe= { 'kin10' ; 'kin16' ; 'kin22'; 'kin28'; 'kin10'; 'kin16'; 'kin22'; 'kin28' };
scapcalc;
cd ..;

```

## C.2 Scapcalcpre.m

```

% scapcalcpre.m : loads in files and does preliminary filtering
% default to not customizing file starts
%custyes =0;
%refframe= { 'kin1'; 'kin1'; 'kin1'; 'kin1'; 'kin1'; 'kin1' ; 'kin1' ;'kin1'; 'kin1'};
% load in configuration values %

endmark= skincor_mark_start -1;
% load in baseline values

for data = 1:numfiles2;
    variable = [ rootname, int2str(data)];
    filename = [variable, extension];
    variable2 = importdata(filename, ',');
    %      eval(['importdata(",filename,",',');']);
%alternate import      a = textread('csv1.csv', "", 'headerlines', 6,'delimiter','');

    variable3 = variable2.data;
    time=(1:size(variable3,1))';
    for h = 2:13;
        Error = variable3(:,h)>=10000;
        Error = Error + (variable3(:,h)<=-10000);
        %if size(time(Error),1)>=20;
        variable3(Error,h)= nan;
        %end
    end
    for h = 2:13;
        oError = variable3(:,h)<=10000;

```

```

oError = oError + (variable3(:,h)>=-10000);
if size(time(Error),1)>=20;
variable3(:,h)= interp1(time(oError),variable3(oError,h),time,'spline');
end
end
for h=humind;
    Error = variable3(:,h)>=10000;
    Error = Error + (variable3(:,h)<=-10000);
    variable3(Error,h)= nan;
end

eval(['kin', num2str(data), ' = variable3 ;'])

clear variable;
clear variable2;
clear variable3;
clear Error;
clear time;
end

%mov_col;
eval([movfile,''])

for data = 1:numfiles2;
    eval(['time=1:(size(kin', num2str(data),',1));']);
    for h=humind;
        eval(['Error = kin',num2str(data),':,h) >=10000;'])
        eval(['Error = Error + (kin',num2str(data),':,h)<=-10000;'])
        eval(['kin',num2str(data),'](Error,h)= nan;'])
    end

```

```

end
clear data;
clear time;
clear Error;

for data = 1:numfiles2;
    eval(['time=1:(size(kin', num2str(data),',1));']);
    eval(['scap_end =size(kin', num2str(data),',2);'])
    for h = startscap:scap_end;
        eval(['Error = kin',num2str(data),':,h) >=10000;'])
        eval(['Error = Error + (kin',num2str(data),':,h)<=-10000;'])
        eval(['kin',num2str(data),'(Error,h)= nan;'])

    end
end
clear data;
clear time;
clear Error;
clear scap_end;
%***** apply butterworth filter

for x = 1:numfiles2;
    eval(['butter(kin',num2str(x),', 4, 30);'])
end

% calculate digitization marks and move files

for x = 1:sum(skincor_num2);
y=skincor_start+x.*3-3;
eval(['msp = kin',num2str(y),':,:;'])
eval(['iap = kin',num2str(y+1),':,:;'])

```

```

eval(['plap = kin','num2str(y+2),':,:];'])
eval(['msp','num2str(y),' = kin','num2str(y),':,:];'])
eval(['iap','num2str(y+1),' = kin','num2str(y+1),':,:];'])
eval(['plap','num2str(y+2),' = kin','num2str(y+2),':,:];'])
scapind= [patch{(size(patch,2)-1)} patch{(size(patch,2)-2)}];
error= isnan(msp(:,[scapind]));
error= sum(error,2);
cut= find(error~=0);
msp([cut],:)=[];

error= isnan(iap(:,[scapind]));
error= sum(error,2);
cut= find(error~=0);
iap([cut],:)=[];

error= isnan(plap(:,[scapind]));
error= sum(error,2);
cut= find(error~=0);
plap([cut],:)=[];

eval(['kin','num2str(skincor_start+x-1),' = digitizer_calc(msp,iap,plap,startdig,endmark);'])

end

for x = 1:nummove2;
    eval(['kin','num2str(sum(skincor_num2)+skincor_start+x-1),' =
kin','num2str(movestart+x-1),';'])
end

skin=mean(kin1);
kin1=mean(kin1);

```

```

% load in digitized points

eval([digfile,'']);
eval([digfile,'2']);
scapdig(5:7,:)= (scapdig(5:7,:)+scapdig2(1:3,:)+scapdig2(4:6,:))./3;
%scapdig(4:6,:)=[skin(:,89:91) ; skin(:,92:94); skin(:,95:97)];

% calculate relative position of digitized markers

kin= kin1;
Tsp_r = kin(:,2:13);
Hum_r = kin(:,humind);
Scap_r = skin(:,startscap:numscapmarkers.*3+startscap-1);

for h = 1:size(patchm,1);
    eval(['patch',num2str(h),'_r = skin(:,patch{',num2str(h),'});'])
end

% Break up files
for i = 1:numfiles;

    eval(['Tsp',num2str(i),' = kin', num2str(i),':,2:13;');
    eval(['Hum',num2str(i),' = kin', num2str(i),':,humind;');
    eval(['Scap',num2str(i),' = kin',num2str(i),':,startscap:numscapmarkers.*3+startscap-1;');
    for h= 1:size(patchm,1);
        eval(['patchm',num2str(h),'_',num2str(i),'=
kin',num2str(i),':,patch{',num2str(h),'});'])
    end

end

```

```

% calculate transformation matrices
for i = 1:sum(skincor_num2)+2;
eval(['Tsp = Tsp',num2str(i),';'])
eval(['Hum = Hum',num2str(i),';'])
eval(['Scap = Scap',num2str(i),';'])

numPts = size(Tsp,1);

for n = 1: numPts;
    o= n ;
    [Tgl_Tsp(:,:,n),Tgl_Tspres(:,:,n)]=soder([Tsp_r(:,:,1);Tsp(o,:)]);
    [Tgl_Hum(:,:,n),Tgl_Humres(:,:,n)]=soder([Hum_r(:,:,1);Hum(o,:)]);
    [Tgl_Scap(:,:,n),Tgl_Scapres(:,:,n)]=soder([Scap_r(:,:,1);Scap(o,:)]);

end

eval(['Tgl_Tsp',num2str(i),' = Tgl_Tsp ;'])
eval(['Tgl_Tspres',num2str(i),' = Tgl_Tsp ;'])
eval(['Tgl_Hum',num2str(i),' = Tgl_Hum ;'])
eval(['Tgl_Humres',num2str(i),' = Tgl_Hum ;'])
eval(['Tgl_Scap',num2str(i),' = Tgl_Scap ;'])
eval(['Tgl_Scapres',num2str(i),' = Tgl_Scap ;'])

clear Tgl_Tsp;
clear Tgl_Hum;
clear Tgl_Scap;
clear Tgl_Tspres;
clear Tgl_Humres;
clear Tgl_Scapres;

```

```

end

%calculate patches separately
for i = 1:sum(skincor_num2)+2;
for h = 1:size(patchm,1);
    eval(['patch',num2str(i),' = patchm',num2str(h),'_',num2str(i),';'])
    eval(['numPts = size(patch',num2str(i),',1);'])
    for n = 1: numPts;
        o= n ;
        eval(['[Tgl_patch',num2str(h),':,:,n],Tgl_patchres',num2str(h),':,:,n]]=soder([patch',n
um2str(h),'_r(:,:,patch',num2str(i),'(o,:));'])
    end

    eval(['Tgl_patch',num2str(h),'_',num2str(i),' = Tgl_patch',num2str(h),';'])
    eval(['Tgl_patchres',num2str(h),'_',num2str(i),' = Tgl_patchres',num2str(h),';'])
    eval(['clear Tgl_patch',num2str(h),';'])
    eval(['clear Tgl_patchres',num2str(h),';'])

end
end

% calculate transformation matrices for config files
Scapc_r = reshape(scadig(5:7,:)',1,9);

for i = skincor_start:skincor_start+sum(skincor_num2)-1;
j = i-skincor_start;

eval(['Scapc',num2str(i),' = kin',num2str(i),':,skincor_mark_start:(skincor_mark_start +
skincor_mark_num -1));'])
end

```

```

%*****=====
% only for trial 1

%mil = [ 1 2 3 4 5 6 7 8 9];
%mli = [ 1 2 3 7 8 9 4 5 6];
%lmi = [ 7 8 9 1 2 3 4 5 6];

%Scapc8= Scapc8(:,mli);
%Scapc12= Scapc12(:,lmi);
%Scapc13= Scapc13(:,lmi);
%Scapc14= Scapc14(:,lmi);

%*****=====

for i = skincor_start:skincor_start+sum(skincor_num2)-1;
    j = i-skincor_start;
    eval(['Scapc = Scapc',num2str(i),';'])
    numPts = size(Scapc,1);
    for n = 1:numPts;
        o=n;
        [Tgl_Scapc(:,:,n),Tgl_Scapcres(:,:,n)]=soder([Scapc_r(:,:,o);Scapc(o,:)]);
    end

    eval(['Tgl_Scapc',num2str(i),' = Tgl_Scapc ;'])
    eval(['Tgl_scapcres',num2str(i),' = Tgl_Scapcres ;'])

    clear Tgl_Scapc;
    clear Tgl_Scapcres;

```

```
end
```

```
%*****  
%*****
```

### C.3 Scapcalc.m

```
% now need to calculate for separate movements with customized starting reference frames
```

```
for cust = 1:nummove2;
```

```
    cust2= cust + movestart2 -1;
```

```
% calculate relative position of digitized markers
```

```
skin= eval([refframe{cust,:}]);
```

```
Scap_r = skin(:,startscap:numscapmarkers.*3+startscap-1);
```

```
for h = 1:size(patchm,1);
```

```
    eval(['patch',num2str(h),'_r = skin(:,patch{',num2str(h),'});'])
```

```
end
```

```
% calculate transformation matrices
```

```
eval(['Tsp = Tsp',num2str(cust2),';'])
```

```
eval(['Hum = Hum',num2str(cust2),';'])
```

```
eval(['Scap = Scap',num2str(cust2),';'])
```

```
numPts = size(Tsp,1);
```

```
for n = 1: numPts;
```

```
o= n ;
```

```
[Tgl_Tsp(:,:,n),Tgl_Tspres(:,:,n)]=soder([Tsp_r(:,:,);Tsp(o,:)]);
```

```
[Tgl_Hum(:,:,n),Tgl_Humres(:,:,n)]=soder([Hum_r(:,:,);Hum(o,:)]);
```

```
[Tgl_Scap(:,:,n),Tgl_Scapres(:,:,n)]=soder([Scap_r(:,:,);Scap(o,:)]);
```

```

end

eval(['Tgl_Tsp',num2str(cust2),' = Tgl_Tsp ;'])
eval(['Tgl_Tspres',num2str(cust2),' = Tgl_Tsp ;'])
eval(['Tgl_Hum',num2str(cust2),' = Tgl_Hum ;'])
eval(['Tgl_Humres',num2str(cust2),' = Tgl_Hum ;'])
eval(['Tgl_Scap',num2str(cust2),' = Tgl_Scap ;'])
eval(['Tgl_Scapres',num2str(cust2),' = Tgl_Scap ;'])

clear Tgl_Tsp;
clear Tgl_Hum;
clear Tgl_Scap;
clear Tgl_Tspres;
clear Tgl_Humres;
clear Tgl_Scapres;

%calculate patches separately
for h = 1:size(patchm,1);
    eval(['patch',num2str(cust2),' = patchm',num2str(h),'_',num2str(cust2),';'])
    eval(['numPts = size(patch',num2str(cust2),',1);'])
    for n = 1: numPts;
        o= n ;
        eval(['[Tgl_patch',num2str(h),':,:,n],Tgl_patchres',num2str(h),':,:,n]=soder([patch',num2str(h),'_r(:,:,);patch',num2str(cust2),'(o,:)]);'])
    end
    eval(['Tgl_patch',num2str(h),'_',num2str(cust2),' = Tgl_patch',num2str(h),';'])
    eval(['Tgl_patchres',num2str(h),'_',num2str(cust2),' = Tgl_patchres',num2str(h),';'])
    eval(['clear Tgl_patch',num2str(h),';'])
    eval(['clear Tgl_patchres',num2str(h),';'])

```

```

end
end
scapcalc2;
%anglecalc;
%export;
anglecalc2;
export;
%anglecalc3;
%export;
%anglecalc4;
%export;
%anglecalc5;
%export;
%anglecalc6;
%export;

```

#### C.4 Scapcalc2.m

```

% second part of scapcalc
% calculates intersegmental angles and such
% change as of april 9, 2003 in order to be able to change reference frames for different
movements, skinrection results will be calculated separately from movements
% Calculate head of the humerus

%eval(['crotH = crot(Hum',num2str(humhead),');'])
%***** only for cadscap
crotH= [(scapdig(4,:))]';
% calculate transformations to anatomical
if scap_side == 1;
Tan_Tsp= mkT([scapdig(2,:)], [scapdig(1,:);scapdig(2,:)], [scapdig(1,:);scapdig(3,:)], 'z','y');
Tan_Scap=mkT([scapdig(5,:)], [scapdig(5,:);scapdig(7,:)], [scapdig(5,:);scapdig(6,:)], 'x','z');

```

```

Tan_Hum =mkT([crotH'],[( scapdig(8,:)+scapdig(9,:))./2;crotH'] , [scapdig(8,:);scapdig(9,:)]
,'z','x');

elseif scap_side == 0;

Tan_Tsp= mkT([scapdig(2,:)], [scapdig(1,:);scapdig(2,:)], [scapdig(1,:);scapdig(3,:)],'z','y');
Tan_Scap=mkT([scapdig(5,:)], [scapdig(7,:);scapdig(5,:)], [scapdig(5,:);scapdig(6,:)],'x','z');
Tan_Hum =mkT([crotH'],[( scapdig(8,:)+scapdig(9,:))./2;crotH'] , [scapdig(9,:);scapdig(8,:)]
,'z','x');

end

% calculate intersegmental transformation matrices

for i = 1:sum(skinCor_num2)+2;

    eval(['numPts=size(Tgl_Tsp',num2str(i),',3);'])

for      n = 1:numPts;

    eval(['T_Tsp_Scap',num2str(i),']( :, :, n) =
inv(Tgl_Tsp',num2str(i),'( :, :, n))*Tgl_Scap',num2str(i),'( :, :, n);'])

    eval(['T_Tsp_Hum',num2str(i),']( :, :, n) =
inv(Tgl_Tsp',num2str(i),'( :, :, n))*Tgl_Hum',num2str(i),'( :, :, n);')

% transform to anatomical

    eval(['T_Tsp_Scap_an',num2str(i),']( :, :, n) =
inv(Tan_Tsp)*T_Tsp_Scap',num2str(i),'( :, :, n)*Tan_Scap ;'])

    eval(['T_Tsp_Hum_an',num2str(i),']( :, :, n) =
inv(Tan_Tsp)*T_Tsp_Hum',num2str(i),'( :, :, n)*Tan_Hum ;'])

for h = 1:size(patchm,1);

```

```

eval(['T_Tsp_patch',num2str(h),'_',num2str(i),':,:,n)=
inv(Tgl_Tsp',num2str(i),':,:,n))*Tgl_patch',num2str(h),'_',num2str(i),':,:,n);'])

%transform to anatomical
eval(['T_Tsp_patch_an',num2str(h),'_',num2str(i),':,:,n)=
inv(Tan_Tsp)*T_Tsp_patch',num2str(h),'_',num2str(i),':,:,n)*Tan_Scap ;'])

end
end
end

% calculate for skin correction (non-anatomical)

for i = skincor_start:skincor_start+sum(skincor_num2)-1;
j = i-skincor_start;
eval(['numPts=size(Tgl_Tsp',num2str(i),',3);'])
for n=1:numPts;
eval(['T_Tsp_Scapc',num2str(i),':,:,n)=
inv(Tgl_Tsp',num2str(i),':,:,n))*Tgl_Scapc',num2str(i),':,:,n);'])

%transform to anatomical
eval(['T_Tsp_Scapc_an',num2str(i),':,:,n)=
inv(Tan_Tsp)*T_Tsp_Scapc',num2str(i),':,:,n)*Tan_Scap ;'])

end
end

% now need to calculate for the separate movement files. This has been modified to allow
for custom reference positions for each movement.

% calculate transformations to anatomical
for cust = 1:nummove2;
cust2= cust + movestart2 -1;
if custyes == 1;

```

```

skin= eval([refframe{cust,:}]);
custma= skin(:,skincor_mark_start:skincor_mark_start+2);
custia= skin(:,skincor_mark_start+3:skincor_mark_start+5);
custpla= skin(:,skincor_mark_start+6:skincor_mark_start+8);

if scap_side == 1;

Tan_Scap=mkT([custma],[custma;custpla],[custma;custia],'x','z');

elseif scap_side == 0;

Tan_Scap=mkT([custma],[custpla;custma],[custma;custia],'x','z');

end
end
% calculate intersegmental transformation matrices
eval(['numPts=size(Tgl_Tsp',num2str(cust2),',3);'])

for n = 1:numPts;
    eval(['T_Tsp_Scap',num2str(cust2),':,:,n)=
inv(Tgl_Tsp',num2str(cust2),':,:,n)*Tgl_Scap',num2str(cust2),':,:,n;'])
    eval(['T_Tsp_Hum',num2str(cust2),':,:,n)=
inv(Tgl_Tsp',num2str(cust2),':,:,n)*Tgl_Hum',num2str(cust2),':,:,n;'])

% transform to anatomical
    eval(['T_Tsp_Scap_an',num2str(cust2),':,:,n)=
inv(Tan_Tsp)*T_Tsp_Scap',num2str(cust2),':,:,n)*Tan_Scap ;'])
    eval(['T_Tsp_Hum_an',num2str(cust2),':,:,n)=
inv(Tan_Tsp)*T_Tsp_Hum',num2str(cust2),':,:,n)*Tan_Hum ;'])

    for h = 1:size(patchm,1);

```

```

eval(['T_Tsp_patch',num2str(h),'_',num2str(cust2),':,:,n)=
inv(Tgl_Tsp',num2str(cust2),':,:,n))*Tgl_patch',num2str(h),'_',num2str(cust2),':,:,n);'])

%transform to anatomical
eval(['T_Tsp_patch_an',num2str(h),'_',num2str(cust2),':,:,n)=
inv(Tan_Tsp)*T_Tsp_patch',num2str(h),'_',num2str(cust2),':,:,n)*Tan_Scap ;'])

end
end
end

```

## C.5 Anglecalc2.m

```

% calculation of euler angle sequences
cd pue
for i = 1:numfiles;
    eval(['numPts = size(Tgl_Tsp',num2str(i),', 3);'])
    for n = 1:numPts;
        eval(['Tsp_ang',num2str(i),'(n,:) = Rxyzsolv(Tgl_Tsp',num2str(i),':,:,n)) ;'])
        eval(['Scap_ang',num2str(i),'(n,:) = Rxyzsolv(T_Tsp_Scap_an',num2str(i),':,:,n)) ;'])
        eval(['Hum_anX',num2str(i), '(n,:) = ryxzsolv(T_Tsp_Hum_an',num2str(i),':,:,n));'])

        eval(['Hum_an',num2str(i), '(n,:) = t2x(T_Tsp_Hum_an',num2str(i),':,:,n) , "rpm"
'),char(39),'; ' ])
        eval(['Hum_an',num2str(i),'(n,5:7) = Hum_an',num2str(i),'(n,5:7).*180./pi;'])

        for h = 1:size(patchm,1);
            eval(['Patch',num2str(h),'_ang',num2str(i),'(n,:) =
Rxyzsolv(T_Tsp_patch_an',num2str(h),'_',num2str(i),':,:,n)) ;'])
        end
        end
    end

```

```

for i = skincor_start:skincor_start+sum(skincor_num2)-1;
    eval(['numPts = size(T_Tsp_Scapc_an',num2str(i),',3);'])
    for n = 1:numPts;
        eval(['ScapC_ang',num2str(i),',(n,:) = Rxyzsolv(T_Tsp_Scapc_an',num2str(i),',( :,n));
    '])
    end
end
for i = 1:numfiles;
    eval(['human = Hum_an',num2str(i),';'])
    human = human';
    eval(['Human_an',num2str(i),'= human ;'])
end

```

## C.6 Export.m

```

% exports data to file
% create output files for movement
for h = 1:nummove2;
    i=movestart2 + h -1;
    if h==3 | 7
        eval(['mov',num2str(h),'=[Tsp_ang',num2str(i),',( :,1:3) Hum_anX',num2str(i),',( :,1:3)
Scap_ang',num2str(i),',( :,1:3) ];'])
    else
        eval(['mov',num2str(h),'=[Tsp_ang',num2str(i),',( :,1:3) Hum_an',num2str(i),',( :,5:7)
Scap_ang',num2str(i),',( :,1:3) ];'])
    end
    for j = 1:size(patchm,1);
        eval(['mov',num2str(h),'=[ mov',num2str(h),'
Patch',num2str(j),'_ang',num2str(i),',( :,1:3) ];'])
    end

```

```

end

% create output files for calibration

l=[];

for h = 1:nummove;

    if h ==1;
        l=0
    else;
        l=l+skincor_num2(h-1);
    end

    if h==3 | 7
        eval(['cal_mov',num2str(h),' = [Tsp_ang1(:,1:3) Hum_anX1(:,1:3) Scap_ang1(:,1:3)
Scap_ang1(:,1:3)];'])
    else
        eval(['cal_mov',num2str(h),' = [Tsp_ang1(:,1:3) Hum_an1(:,5:7) Scap_ang1(:,1:3)
Scap_ang1(:,1:3)];'])
    end

    for i = 1:skincor_num2(h);

        j= skincor_start + (i-1) + l;

        if h ==3 | 7
            eval(['cal_mov',num2str(h),' = [ cal_mov',num2str(h),' ;
Tsp_ang',num2str(j),':,1:3) Hum_anX',num2str(j),':,1:3) Scap_ang',num2str(j),':,1:3)
ScapC_ang',num2str(j),':,1:3) ];'])
        else
            eval(['cal_mov',num2str(h),' = [ cal_mov',num2str(h),' ;
Tsp_ang',num2str(j),':,1:3) Hum_an',num2str(j),':,5:7) Scap_ang',num2str(j),':,1:3)
ScapC_ang',num2str(j),':,1:3) ];'])
        end
    end
end

```

```

% build patch side of matrix
% start with empty matrices
for h = 1:nummove;
    eval(['ptchs',num2str(h),' = [];'])
    for k = 1:skincor_num2(h);
        eval(['ptchs',num2str(h),'_',num2str(k),' = [];'])
    end
end

% add patches horizontally
for h = 1:nummove;
    for j = 1:size(patchm,1);
        eval(['ptchs',num2str(h),' = [ ptchs',num2str(h),''
Patch',num2str(j),'_ang1(:,1:3)];'])
    end
end

l = [];
for h = 1:nummove;
    if h ==1;
        l=0
    else;
        l=l+skincor_num2(h-1);
    end
    for j = 1:size(patchm,1);
        for k = 1:skincor_num2(h);
            m= skincor_start + (k-1) +l;
            eval(['ptchs',num2str(h),'_',num2str(k),' = [
ptchs',num2str(h),'_',num2str(k),' Patch',num2str(j),'_ang',num2str(m),':,1:3 ];'])
        end
    end
end

```

```

for h = 1:nummove;
    for k = 1:skincor_num2(h);
        eval(['ptchs',num2str(h),' = [ ptchs',num2str(h),'; ;
ptchs',num2str(h),'_',num2str(k),'; ];'])
    end
end
for h = 1: nummove;
    eval(['cal_mov',num2str(h),' = [ cal_mov',num2str(h),'; ptchs',num2str(h),'; ];'])
end
% output files labelled: Thoracic, Humerus, Scapula, Scapula corrected, Patch.n, Patch.1
corrected

% write files to disk
for h = 1:nummove;
eval(['save ',rootname,'cal_mov',num2str(h),'.txt cal_mov',num2str(h),' -ASCII;'])
end

for h = 1:nummove2;
eval(['save ',rootname,'_mov',num2str(h),'.txt mov',num2str(h),' -ASCII;'])
end

% data for calculation of accuracy/reliability of skin digitizing.
%X =[]
%for h= skincor_start:skincor_start+skincor_num-1;
%eval(['X = [ X ;mean(Patch1_ang',num2str(h),':,1:3));
mean(ScapC_ang',num2str(h),':,1:3))];'])

%end
%eval(['save ',rootname,'_skin_mov.txt X -ASCII;'])
cd ..

```

## C.7 Skincor\_all.m.m

```
% skin correction factor. Calculates based on raw movement data.  
clear all;  
close all;  
workdir=pwd;  
  
%for direction= ['d' 'u']  
%direction= 'u'  
for trial={ '1' '2p'};  
%trial='2p'  
  
if strcmp(trial{1},'2p') == 1  
  
subs= {  
    'sub1'  
    'sub2'  
    'sub3'  
    'sub4'  
    'sub5'  
    'sub6'  
    'sub7'  
    'sub8'  
};  
  
ref= {  
    [ 1 2 3 4 5 6 7 ]  
    [ 1 2 3 4 5 6]  
    [ 1 2 3 4 5 6]  
    [ 1 2 3 4 5 6]  
    [ 1 2 3 4 5 6]
```

```

[ 1 2 3 4 5 6]
[ 1 2 3 4 5 6]
[ 1 2 3 4 5 6]

};

calperMov= {
[ 8 6 6 6]
[ 6 6 6 6]
%[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
[ 6 6 6 6]
};

cal_match={ [ 2 3 4 5 8 10] [2 3 11 12 13 14 15 16] [ 2 3 17 18 19 20 21 22] [ 23 24 25 26
27 28]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
[ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
};

ref_match={
[ 0 1 2 3 6 7]+1 [0 1 2 3 4 5 6 7]+1 [ 0 1 2 3 4 5 6 7 ]+1 [ 2 3 4 5 6 7]+1
[ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1

```

```

[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
};

else
% these lines of code have not been verified to be correct
subs= {
    'sub1'
    'sub2'
    'sub3'
    'sub4'
    'sub5'
    'sub6'
    'sub7'
    'sub8'
};

ref= {
    [ 1 2 3 4 5 6 7 8]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
    [ 1 2 3 4 5 6]
};

};
```

```

calperMov= {
    [ 6 6 8 5]
    [ 6 6 6 6]
    [ 6 6 6 6]
    [ 6 6 6 6]
    [ 5 6 6 6]
    [ 6 6 6 6]
    [ 6 6 6 6]
    [ 6 6 6 6]
};

cal_match= {
    [ 2 3 4 7 8 22] [2 9 10 11 12 13 14 22] [2 15 16 17 18 19 20 22] [ 23 24 25 26 27 ]


```

```

    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 5 7 ] [2 8 9 10 11 12 13 ] [2 14 15 16 17 18 19 ] [ 20 21 22 23 24 25 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
    [ 2 3 4 7 8] [2 9 10 11 12 13 14] [2 15 16 17 18 19 20] [ 21 22 23 24 25 26 ]
};


```

```

ref_match={

    [ 0 1 2 5 6 7]+1 [0 1 2 3 4 5 6 7]+1 [ 0 1 2 3 4 5 6 7 ]+1 [ 1 2 3 4 5 ]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
    [ 0 1 2 5 6]+1 [0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1
}


```

```

[ 0 1 2 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 0 1 2 3 4 5 6]+1 [ 1 2 3 4 5 6]+1

};

end

%load the files in

for h= 1:size(cal_match,1);

    for i=1:size(cal_match,2);

        cal_match{h,i}=cal_match{h,i}- 1;

    end

end

for h= 1:size(subs,1);

    x=[];

    for i=1:4;

        %if i==1 | i==2;

        %    p=5;

        %else

        %    p=6;

        %end

        cd pue;

        x{1}=load([' subs{h} trial{1} '_mov' num2str(i) '.txt']);

        x{1}(x{1}<=-150)=180+ 180 + x{1}(x{1}<=-150);

        cd ..;

        for j=1:size(ref{h},2)

            eval(['cd ref', num2str(ref{h}(j)), '/pue'])

            x{(ref{h}(j)+1)}=load([' subs{h} trial{1} '_mov' num2str(i) '.txt']);

            x{(ref{h}(j)+1)}(x{(ref{h}(j)+1)}<=-150)=180+ 180 +

            x{(ref{h}(j)+1)}(x{(ref{h}(j)+1)}<=-150);

            cd ../../;

        end

    end

```

```

for j=1:4;
    cd pue;
    cal{j}=load([ subs{h} trial{1} 'cal_mov' num2str(j) '.txt']);
    cd ..;
end;
cal2=[];
cal2(1,:)=cal{1}(1,:);
for j=1:4;
    cal2=[cal2;cal{j}(2:end,:)];
end

% create coefficients
movecor=zeros(size(x{ref_match{h,i}{1}}));

if i==1;
    for k=1:size(x{1},1);
        part=[];
        cox=[];
        for j = 1:size(cal_match{h,i},2);
            if abs(cal2(cal_match{h,i}{j},5)-
x{ref_match{h,i}{j}}(k,5))>=100
                cox(j)=0;
            else
                cox(j)= 1 - abs((cal2(cal_match{h,i}{j},5)-
x{ref_match{h,i}{j}}(k,5))./100);
            end
            part(j,:)=x{ref_match{h,i}{j}}(k,:).*cox(j);
        end
        movecor(k,:)=sum(part)./sum(cox);
    end

elseif i==2;

```

```

for k=1:size(x{1},1);
    part=[];
    cox=[];
    for j = 1:size(cal_match{h,i},2);
        if abs(cal2(cal_match{h,i}(j),5)-
x{ref_match{h,i}(j)}(k,5).*2)>=100
            cox(j)=0;
        else
            cox(j)= 1 - abs((cal2(cal_match{h,i}(j),5)-
x{ref_match{h,i}(j)}(k,5))./100.*2);
        end
        part(j,:)=x{ref_match{h,i}(j)}(k,:).*cox(j);
    end
    movecor(k,:)=sum(part)./sum(cox);
end
elseif i==3;

for k=1:size(x{1},1);
    part=[];
    cox=[];
    for j = 1:size(cal_match{h,i},2);
        if abs(cal2(cal_match{h,i}(j),6)-
x{ref_match{h,i}(j)}(k,6))>=100
            cox(j)=0;
        else
            cox(j)= 1 - abs((cal2(cal_match{h,i}(j),6)-
x{ref_match{h,i}(j)}(k,6))./100);
        end
        part(j,:)=x{ref_match{h,i}(j)}(k,:).*cox(j);
    end

```

```

        end
        movecor(k,:)=sum(part)./sum(cox);
    end

else

    for k=1:size(x{1},1);
        part=[];
        cox=[];
        for j = 1:size(cal_match{h,i},2);
            if abs(cal2(cal_match{h,i}(j),6)-
x{ref_match{h,i}(j)}(k,6))>=100
                cox(j)=0;
            else
                cox(j)= 1 - abs((cal2(cal_match{h,i}(j),6)-
x{ref_match{h,i}(j)}(k,6))./100);
            end
            part(j,:)=x{ref_match{h,i}(j)}(k,:).*cox(j);
        end
        movecor(k,:)=sum(part)./sum(cox);
    end

end

% apply coefficient to movement
movecor2=zeros(size(x{1},1),3);
for j=1:size(ref_match{h,i},2);
    movecor2=movecor2 + x{ref_match{h,i}(j)}(:,end-2:end);
end
movecor2= movecor2./size(ref_match{h,i},2);
movecor=[movecor movecor2];

```

```

    save([ workdir '/' subs{h} trial{1} '_mov' num2str(i) '_m_cor.txt ],'movecor','-
ASCII')

```

```

end

```

```

end

```

```

end

```

```

%end

```

## C.8 Norms\_h\_cor.m

```

% norms
workdir= pwd;
rootname2={ 'ac1' 'ac2p' 'em1' 'em2p' 'si1' 'si2p' 'mc1' 'mc2p' 'jh1' 'jh2p' 'md1' 'md2p' 'hp1'
'hp2p' 'ca1' 'ca2p'};;
rootname2={ 'hp1'};
numove2= ones(1,size(rootname2,2)).*4;
dir = { 'scapstat'};

for j=1:size(dir,2);
    eval(['cd ',dir{j}])
    for xxx = 1:size(numove2,2);
        nummove2=numove2(xxx) ;
        rootname=rootname2{xxx};
        for i = 1:nummove2;
            eval(['load ',rootname,'_mov',num2str(i),'_m_cor.txt;'])
        end
        normconfig4;
    end
    eval(['cd ', workdir]);
end

```

### C.9 Normconfig4.m

```
% config file for each movement normalization
% u is the up direction d is the return direction
for x = 1:nummove2;
    eval(['mov = ',rootname,'_mov',num2str(x),'_m_cor;'])
    inter='_mov';
    ending='_point.txt';
    filename= [rootname,inter,int2str(x),ending];
    normdata = importdata(filename);
    normdata = round(normdata);

    if x == 3;
        if strcmp(rootname,'jess1')==1;
            normdata(size(normdata,1),:)=[];
            %elseif strcmp(rootname,'jacq2')==1
            %normdata(size(normdata,1),:)=[];
        end
    end

    if normdata(1)<=0;
        normdata(1)=1;
    end

    if normdata(size(normdata,1),1) >= size(mov,1);
        normdata(size(normdata,1),1)=size(mov,1);
    end

    numswing= (size(normdata,1))/3;
    normdata= normdata(:,1);
    normdata= reshape(normdata,3,numswing');
```

```

normdatau= normdata(:,1:2);
normdatad= normdata(:,2:3);
mov2=[];
mov3=[];
movnormu_av=[];
movnormd_av=[];
for xx=1:size(normdatau,1);

    mov2=[mov([normdatau(xx,1):normdatau(xx,2)],:)];
    mov3=[mov([normdatad(xx,1):normdatad(xx,2)],:)];

% need to remove missing humeral data when all angles = 0

    miss= sum(mov2(:,4:6),2);
    miss= find(miss);
    mov2=mov2(miss,:);
    miss= sum(mov3(:,4:6),2);
    miss= find(miss);
    mov3=mov3(miss,:);
    % end of humeral fix

    if x==4 |x==3
        p=6;
    else;
        p=5;
        mov2(mov2<=-150)=180 + 180 +mov2(mov2<=-150);
        mov3(mov3<=-150)=180 + 180 +mov3(mov3<=-150);
    end

    [garb,indu]=sort(mov2(:,p));
    [garb,indd]=sort(mov3(:,p));

```

```

mov2=mov2([indu],:);
mov2(isnan(mov2(:,p)),:)=[];
mov3=mov3([indd],:);
mov3(isnan(mov3(:,p)),:)=[];

indu2=[ ceil(min(mov2(:,p))./1):1:floor(max(mov2(:,p))./1) ];
indd2=[ ceil(min(mov3(:,p))./1):1:floor(max(mov3(:,p))./1) ];

% mov2=resample(mov2,15,30);
% mov3=resample(mov3,15,30);
movnormu_av(:,:,xx)= zeros(240,size(mov2,2)).*nan;
movnormd_av(:,:,xx)= zeros(240,size(mov3,2)).*nan;

% need to make sure that there is not two H angles exactly the same
for cons= 2:size(mov2,1);
    if mov2(cons,p)==mov2(cons-1,p);
        mov2(cons,p)=mov2(cons,p) + 0.00001;
    end
end

for cons= 2:size(mov3,1);
    if mov3(cons,p)==mov3(cons-1,p);
        mov3(cons,p)=mov3(cons,p) + 0.00001;
    end
end

movnormu_avI=[interp1(mov2(:,p),mov2,indu2)];
movnormd_avI=[interp1(mov3(:,p),mov3,indd2)];
```

if p==5

```

movnormu_av((movnormu_avI(1,p)+40):(movnormu_avI(end,p)+40),:,xx)=movnor
mu_avI;

movnormd_av((movnormd_avI(1,p)+40):(movnormd_avI(end,p)+40),:,xx)=movnor
md_avI;

else

movnormu_av((movnormu_avI(1,p)+150):(movnormu_avI(end,p)+150),:,xx)=movno
rnu_avI;

movnormd_av((movnormd_avI(1,p)+150):(movnormd_avI(end,p)+150),:,xx)=movno
rmd_avI;

end

end

mov_isnanu=isnan(movnormu_av);
mov_isnand=isnan(movnormd_av);
movnormu_av(mov_isnanu)=0;
movnormd_av(mov_isnand)=0;
movnou=movnormu_av;
movnod=movnormd_av;
movnormu_av=sum(movnormu_av,3)./(ones(size(movnormu_av,1),size(movnormu_
av,2)).*size(movnormu_av,3)-sum(mov_isnanu,3));
movnormd_av=sum(movnormd_av,3)./(ones(size(movnormd_av,1),size(movnormd_
av,2)).*size(movnormd_av,3)-sum(mov_isnand,3));
eval(['save ',workdir,'/',dir{j}, '/',rootname,'_mov',num2str(x),'_m_cor_normu_av_h.txt
movnormu_av -ASCII;'])

eval(['save ',workdir,'/',dir{j}, '/',rootname,'_mov',num2str(x),'_m_cor_normd_av_h.txt
movnormd_av -ASCII;'])

movnormu_av=[];
movnormd_av=[];

end

```

## Appendix D RMS Errors and Differences

### D.1 Effect of Pins per Patch

The tables below show the rms difference between the patch values with the pins in and the patch values without the pins. All values are in degrees.

**Patch 1**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	3.94	1.92	3.90
Reaching	3.35	1.43	4.35
Hand Behind Back	2.63	2.97	1.97
Horizontal Adduction	4.19	1.73	5.26

**Patch 2**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.43	1.80	4.11
Reaching	3.61	1.03	4.22
Hand Behind Back	2.45	1.88	2.48
Horizontal Adduction	3.98	2.33	4.81

**Patch 3**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	3.83	1.80	3.77
Reaching	3.20	1.08	4.37
Hand Behind Back	2.82	1.69	3.32
Horizontal Adduction	3.14	2.49	4.18

**Patch 4**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.15	1.56	4.00
Reaching	3.42	1.07	4.36
Hand Behind Back	2.49	2.15	2.14
Horizontal Adduction	4.02	2.18	4.99

**Patch 5**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.23	1.61	4.02
Reaching	3.39	1.01	4.31
Hand Behind Back	2.40	1.51	2.82
Horizontal Adduction	3.61	2.54	4.66

**Patch 6**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.23	1.61	4.02
Reaching	3.39	1.01	4.31
Hand Behind Back	2.40	1.51	2.82
Horizontal Adduction	3.61	2.54	4.66

## D.2 RMS Errors for Each Patch

The tables below show the rms error between the corrected patch values and the bone pins.

All values are in degrees.

**Patch 1**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	2.9	3	2.4
Reaching	4	2.5	2
Hand Behind Back	2.8	2	2
Horizontal Adduction	1.9	1.9	2.5

**Patch 2**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	2.4	2.75	3.2
Reaching	2.2	2	2.4
Hand Behind Back	2.2	1.7	3.2
Horizontal Adduction	1.8	2.3	2.7

**Patch 3**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	3	3.2	4.7
Reaching	2.1	2.7	3.6
Hand Behind Back	5.1	2.3	5.2
Horizontal Adduction	1.5	2.7	3.1

**Patch 4**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	2.34	2.8	2.8
Reaching	3	2	2.2
Hand Behind Back	2	1.6	2.3
Horizontal Adduction	1.7	2.1	2.6

**Patch 5**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	2.3	2.95	3.6
Reaching	1.8	2.2	2.8
Hand Behind Back	3.3	2	4.1
Horizontal Adduction	1.6	2.6	2.8

**Patch 6**

	Posterior Tipping	Upward Rotation	Internal Rotation
Abduction	2.2	2.8	2.9
Reaching	2.3	2	2.4
Hand Behind Back	2.2	1.8	2.8
Horizontal Adduction	1.6	2.3	2.6

**D.3 RMS Differences for Each Patch: Day One vs. Day Two**

The tables below show the rms differences between the corrected values on day one and the corrected values on day two. All values are in degrees.

**Patch 1**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	2.64	6.18	6.71
Reaching	4.81	3.96	7.07
Hand Behind Back	3.88	4.52	6.04
Horizontal Adduction	6.11	4.39	5.56

**Patch 2**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.02	5.87	7.39
Reaching	3.96	3.76	7.18
Hand Behind Back	4.71	4.60	6.90
Horizontal Adduction	5.61	4.62	5.51

**Patch 3**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.92	6.20	8.05
Reaching	3.96	3.88	7.59
Hand Behind Back	6.19	4.45	7.71
Horizontal Adduction	5.14	5.02	5.46

**Patch 4**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	3.07	6.10	7.23
Reaching	4.10	3.89	7.17
Hand Behind Back	3.92	4.67	6.40
Horizontal Adduction	5.76	4.78	5.47

**Patch 5**

	Posterior Tipping	Upward Rotation	External Rotation
Abduction	4.18	6.21	7.53
Reaching	3.76	3.93	7.32
Hand Behind Back	5.24	4.72	7.20
Horizontal Adduction	5.38	5.11	5.61

**Patch 6**

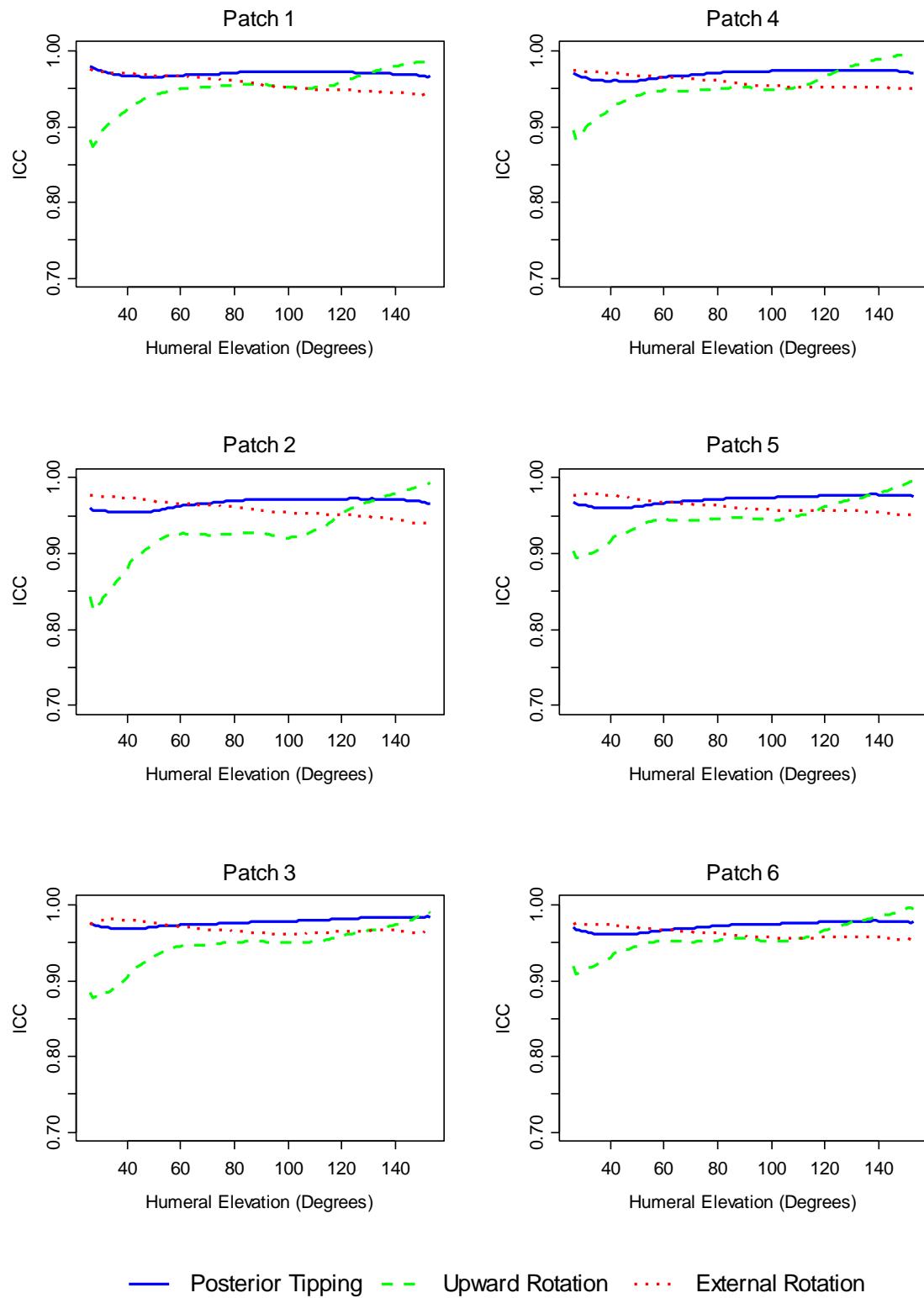
	Posterior Tipping	Upward Rotation	External Rotation
Abduction	3.42	6.23	7.33
Reaching	3.86	3.96	7.22
Hand Behind Back	4.35	4.73	6.67
Horizontal Adduction	5.55	5.02	5.55

## **Appendix E Graphs**

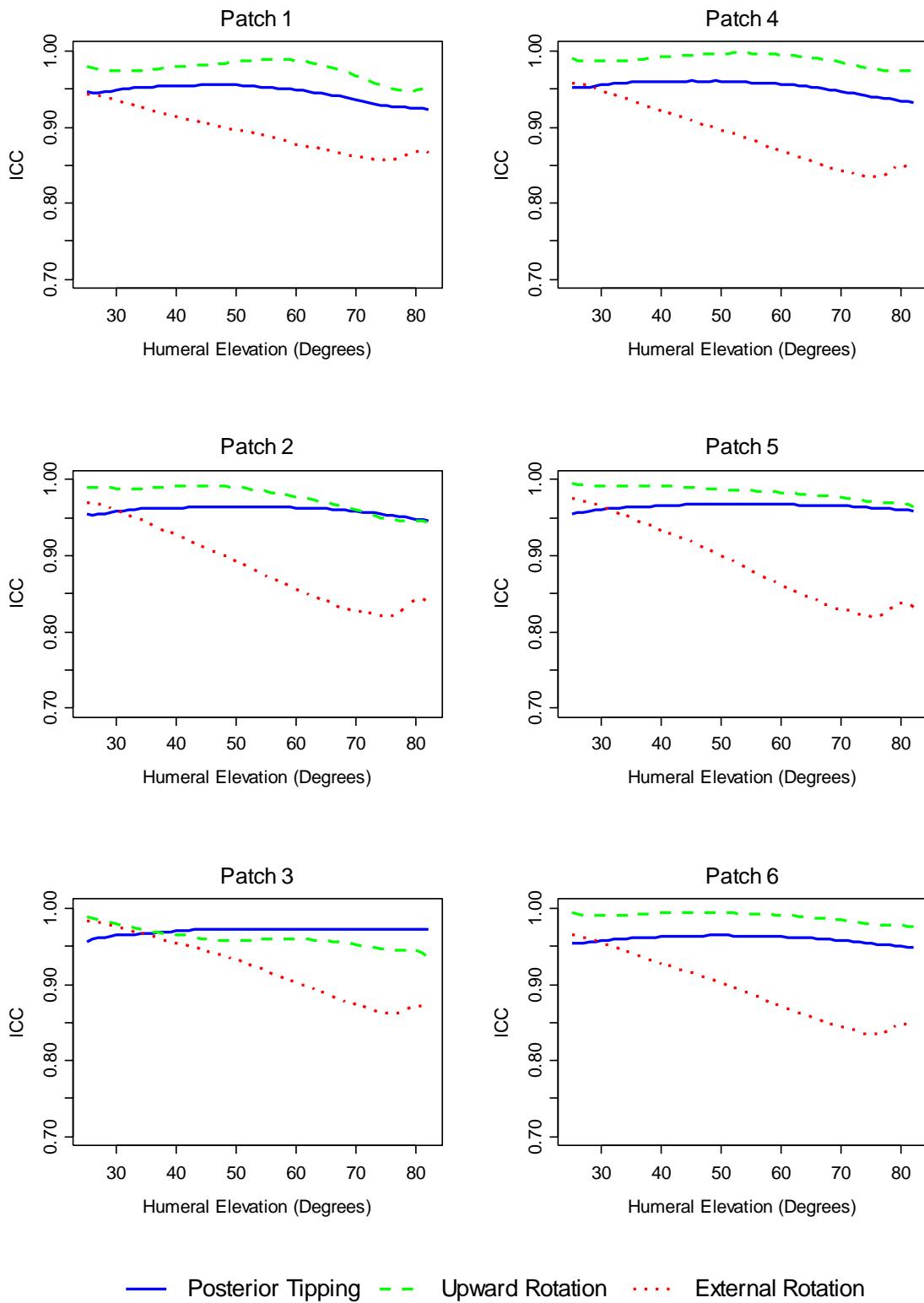
### **E.1 Effect of Pins per Patch**

The graphs on the following pages show the ICC(3,10) between the patches with the pins in and the patches without the pins.

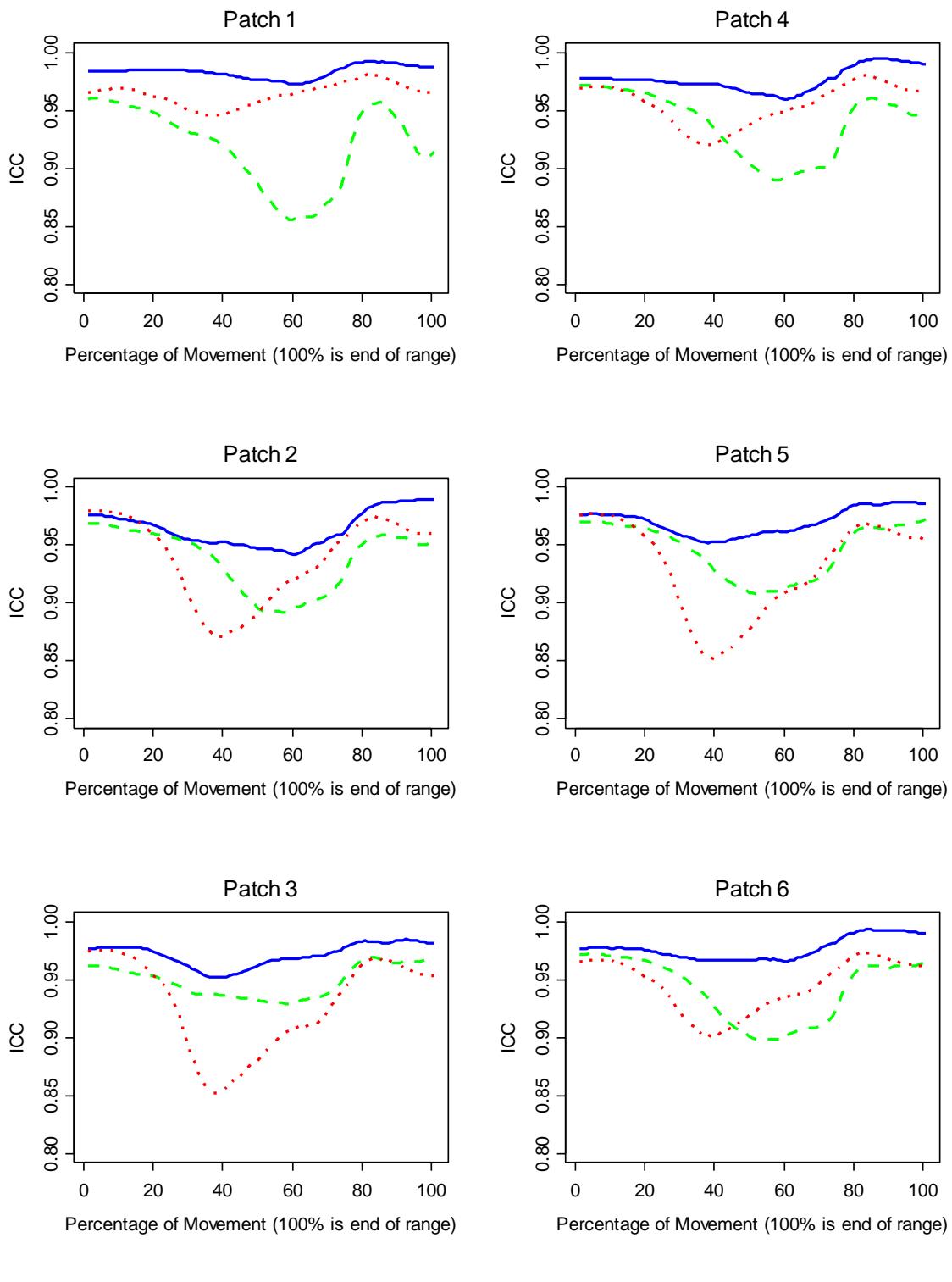
## Abduction: Effect of Pins on Patch



## Reaching: Effect of Pins on Patch

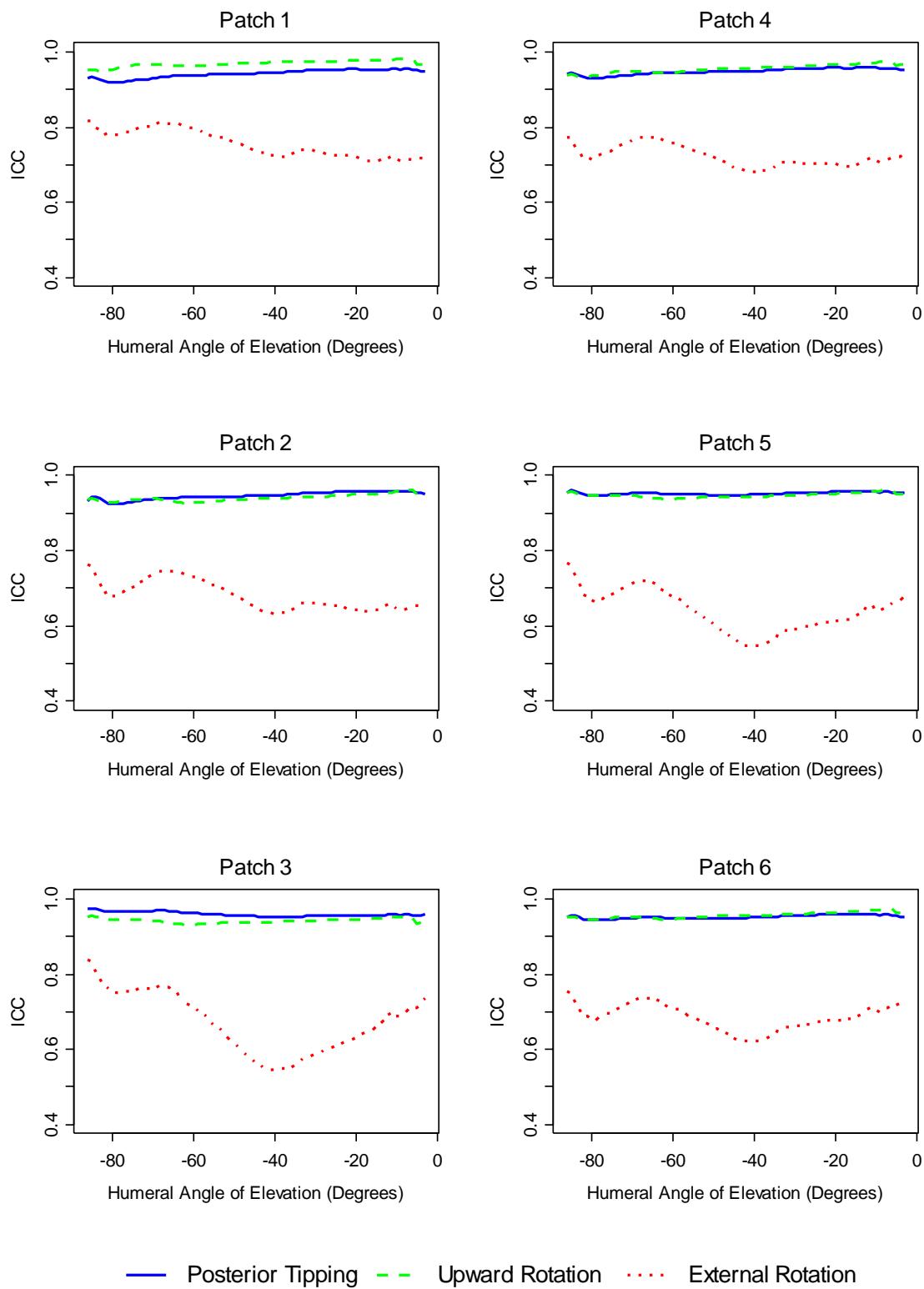


## Hand Behind Back: Effect of Pins on Patch



— Posterior Tipping    - - - Upward Rotation    ... External Rotation

## Horizontal Adduction: Effect of Pins on Patch

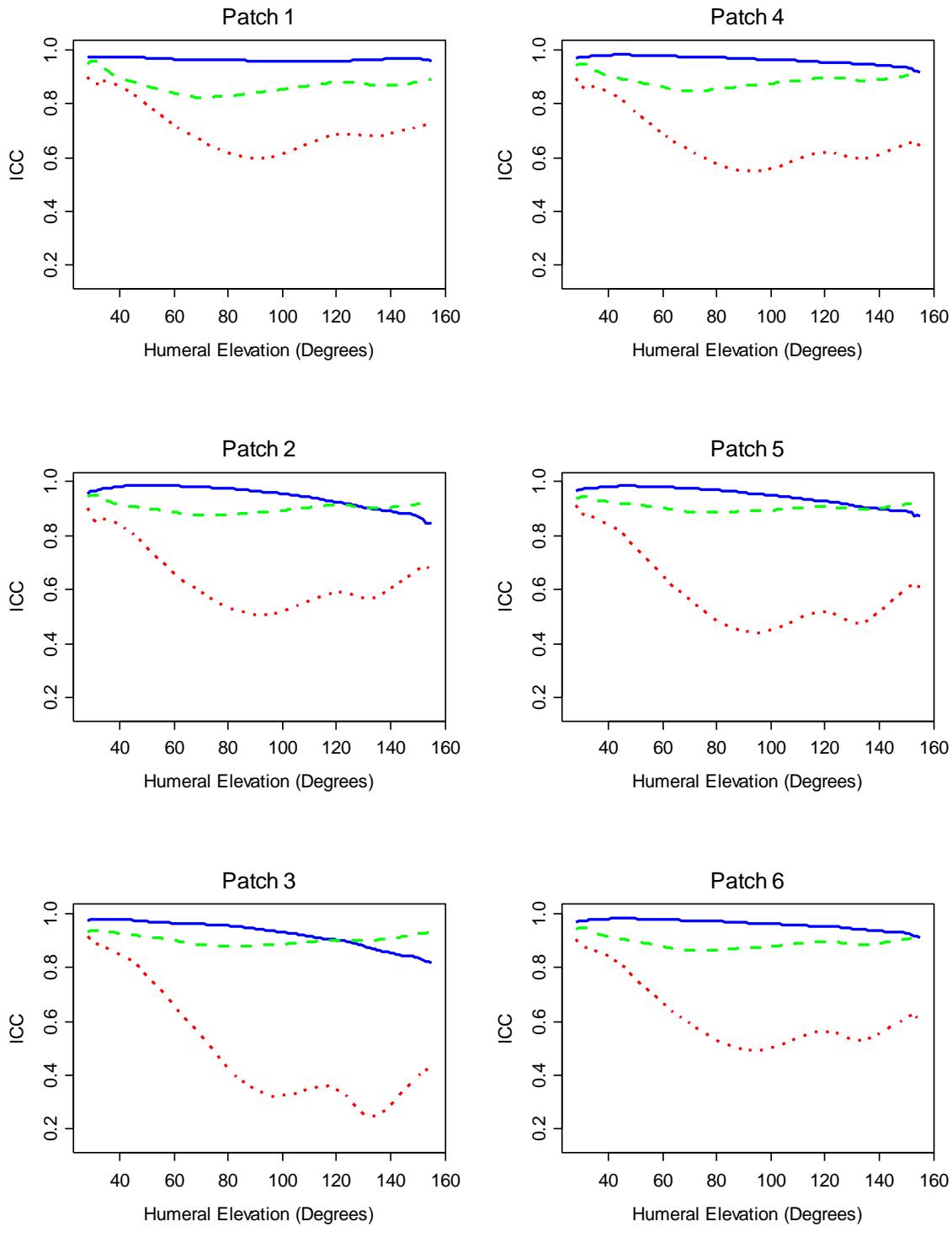


— Posterior Tipping    - - - Upward Rotation    ····· External Rotation

## **E.2 Test-retest Reliability**

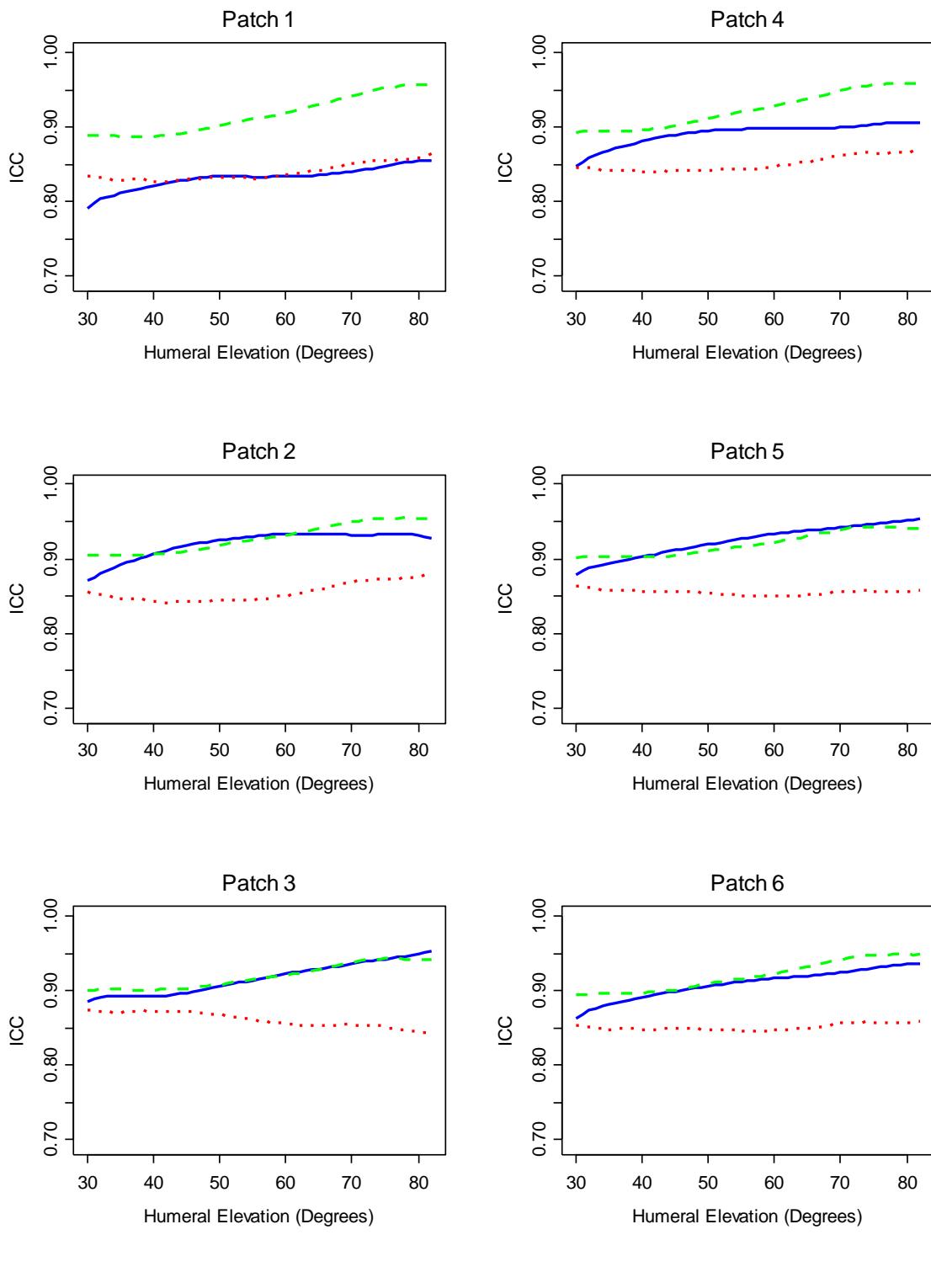
The graphs on the following pages show the ICC(3,10) between the corrected scapular motion on day one and the corrected scapular motion on day two.

## Abduction: Test-retest Reliability of Patches



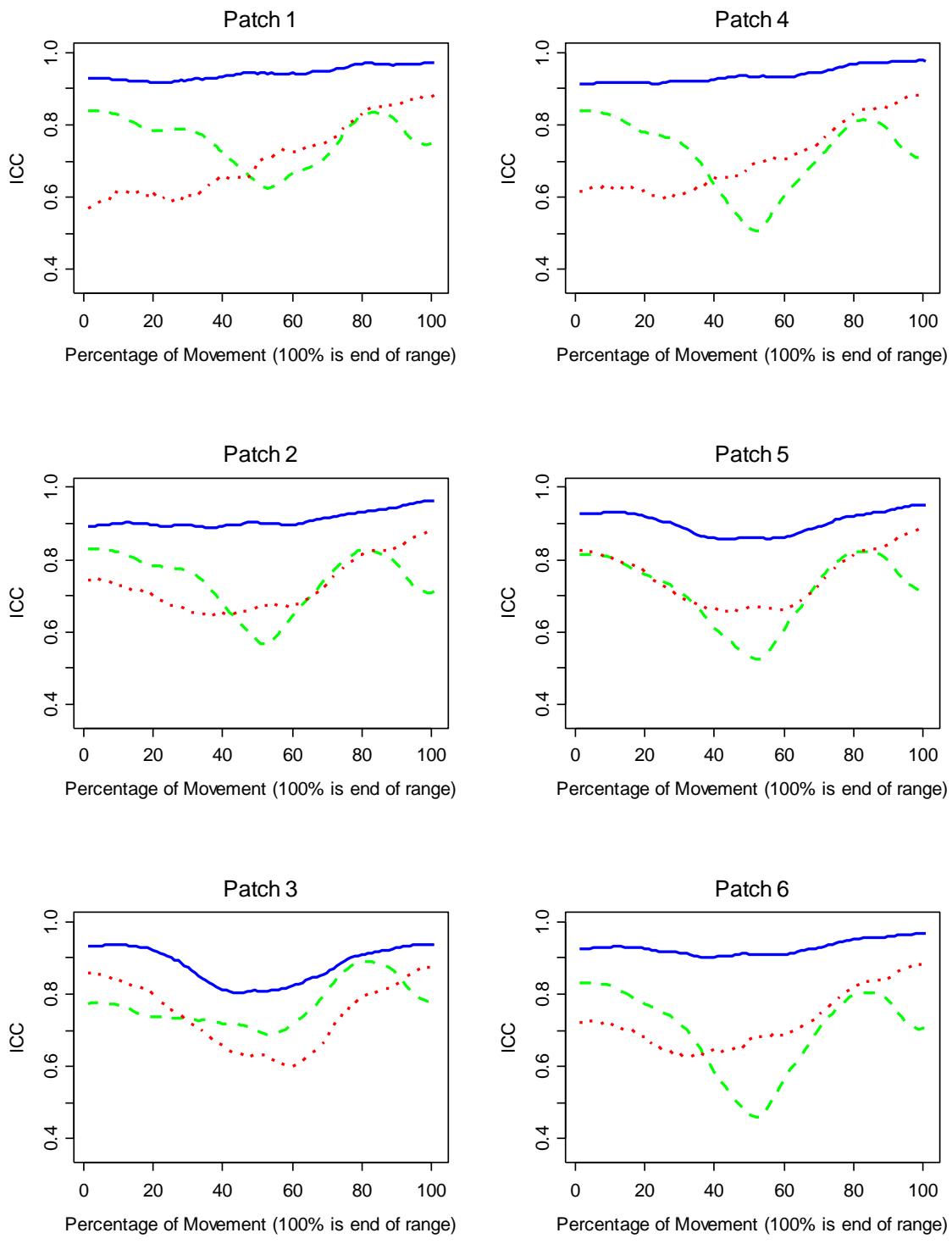
— Posterior Tipping    - - - Upward Rotation    ... External Rotation

## Reaching: Test-retest Reliability of Patches



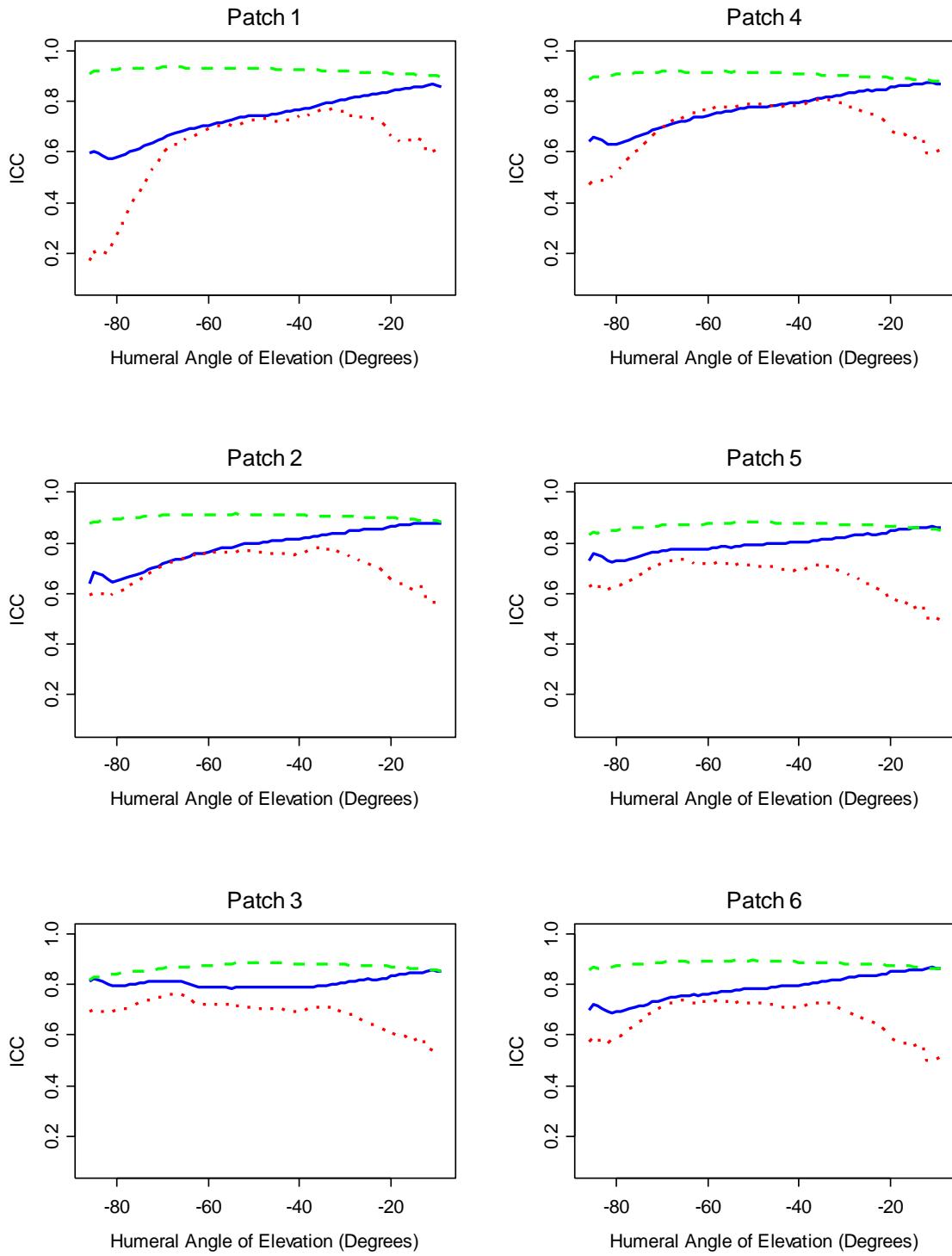
— Posterior Tipping    - - - Upward Rotation    ... External Rotation

## Hand Behind Back: Test-retest Reliability of Patches



— Posterior Tipping   - - - Upward Rotation   ... External Rotation

## Horizontal Adduction: Test-retest Reliability of Patches



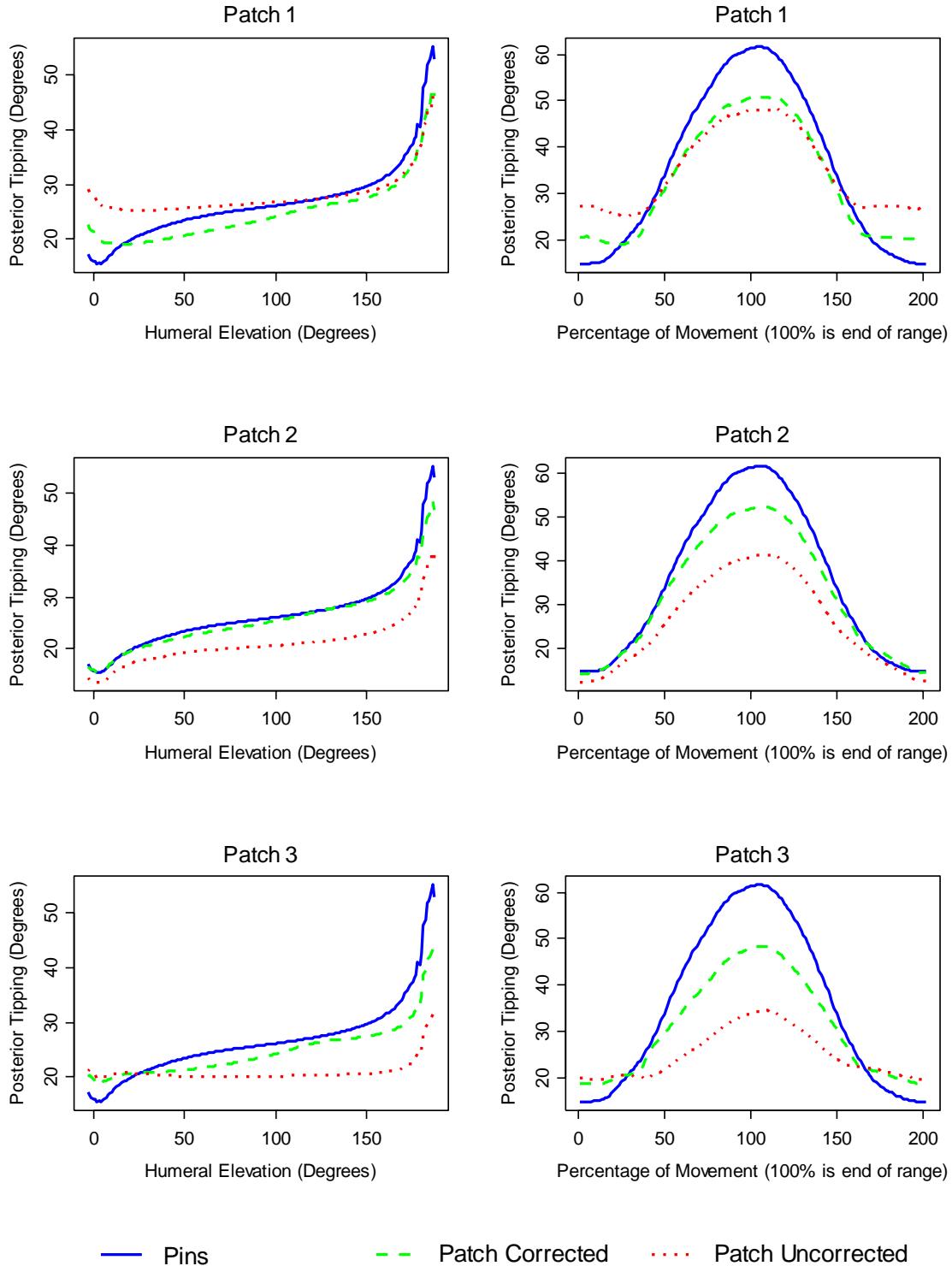
— Posterior Tipping    - - - Upward Rotation    ... External Rotation

### **E.3 Pins vs. Uncorrected and Corrected Patches**

The graphs on the following pages show the movement of the scapula as recorded by the pins, the corrected patches and the uncorrected patches. The graphs on the left of the page are normalized to humeral motion and the graphs on the right of the page are normalized to percentage of movement.

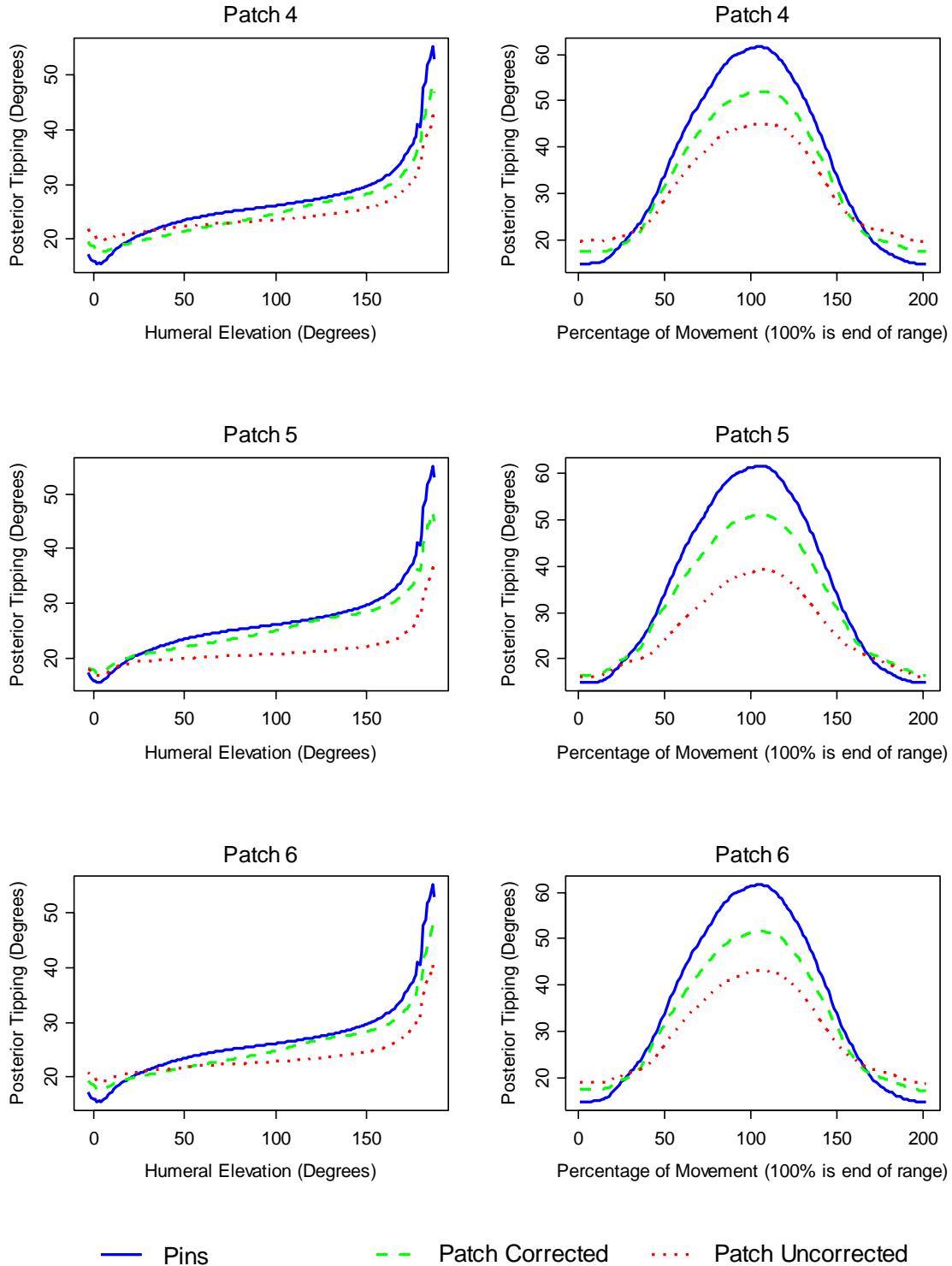
# Abduction: Pins vs. Patches Subject1

## Posterior Tipping

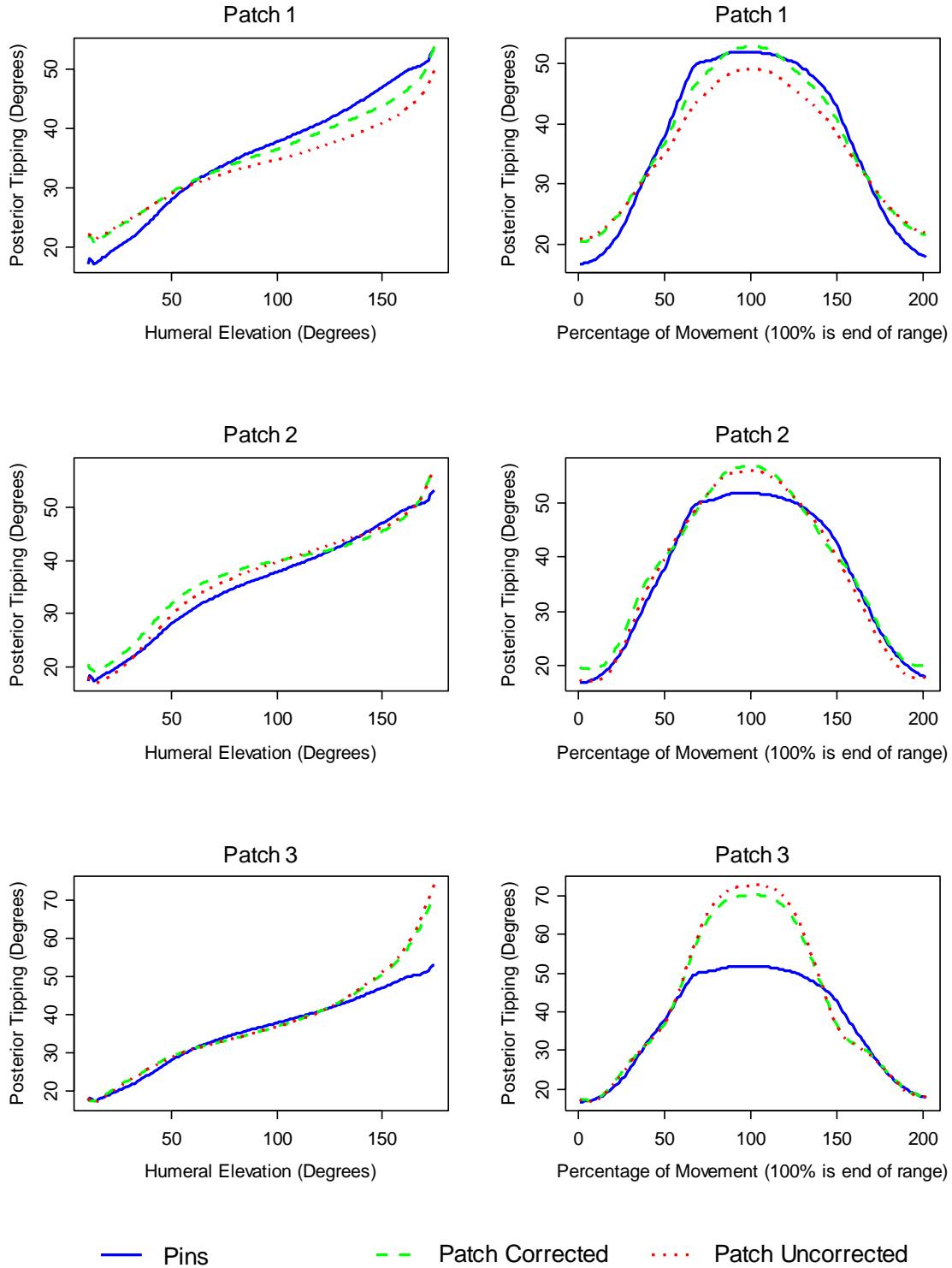


# Abduction: Pins vs. Patches Subject1

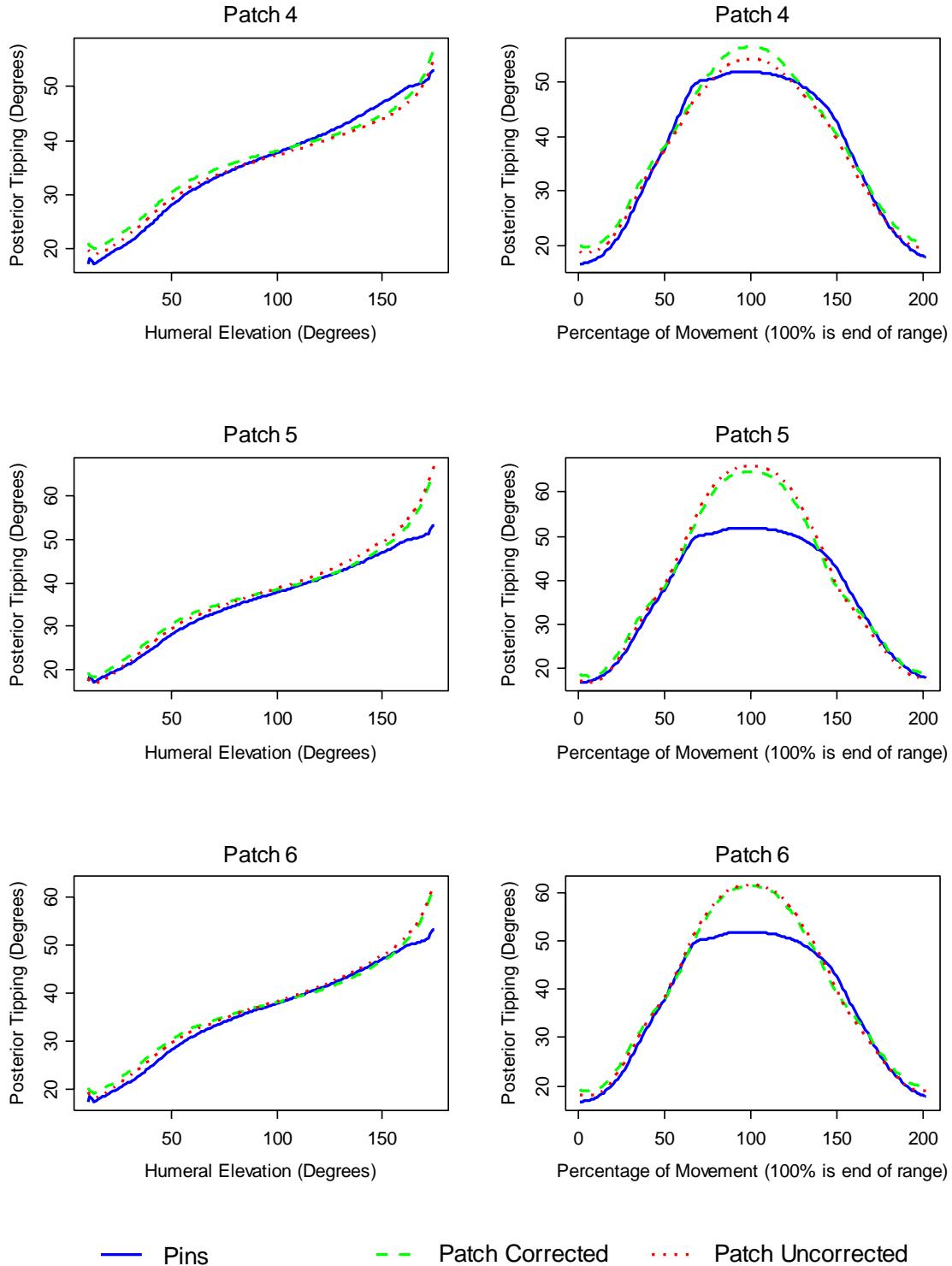
## Posterior Tipping



## Abduction: Pins vs. Patches Subject2 Posterior Tipping

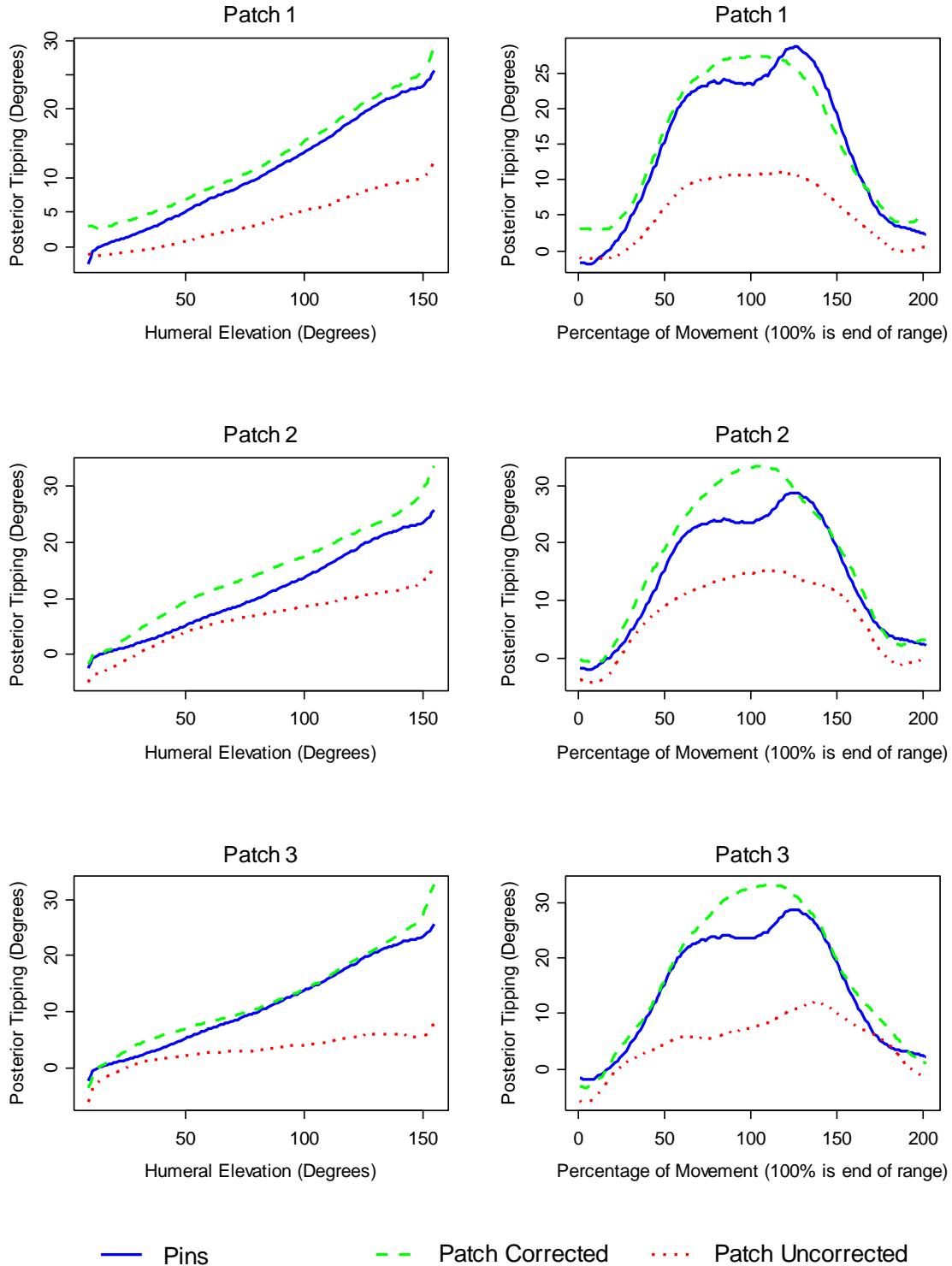


## Abduction: Pins vs. Patches Subject2 Posterior Tipping



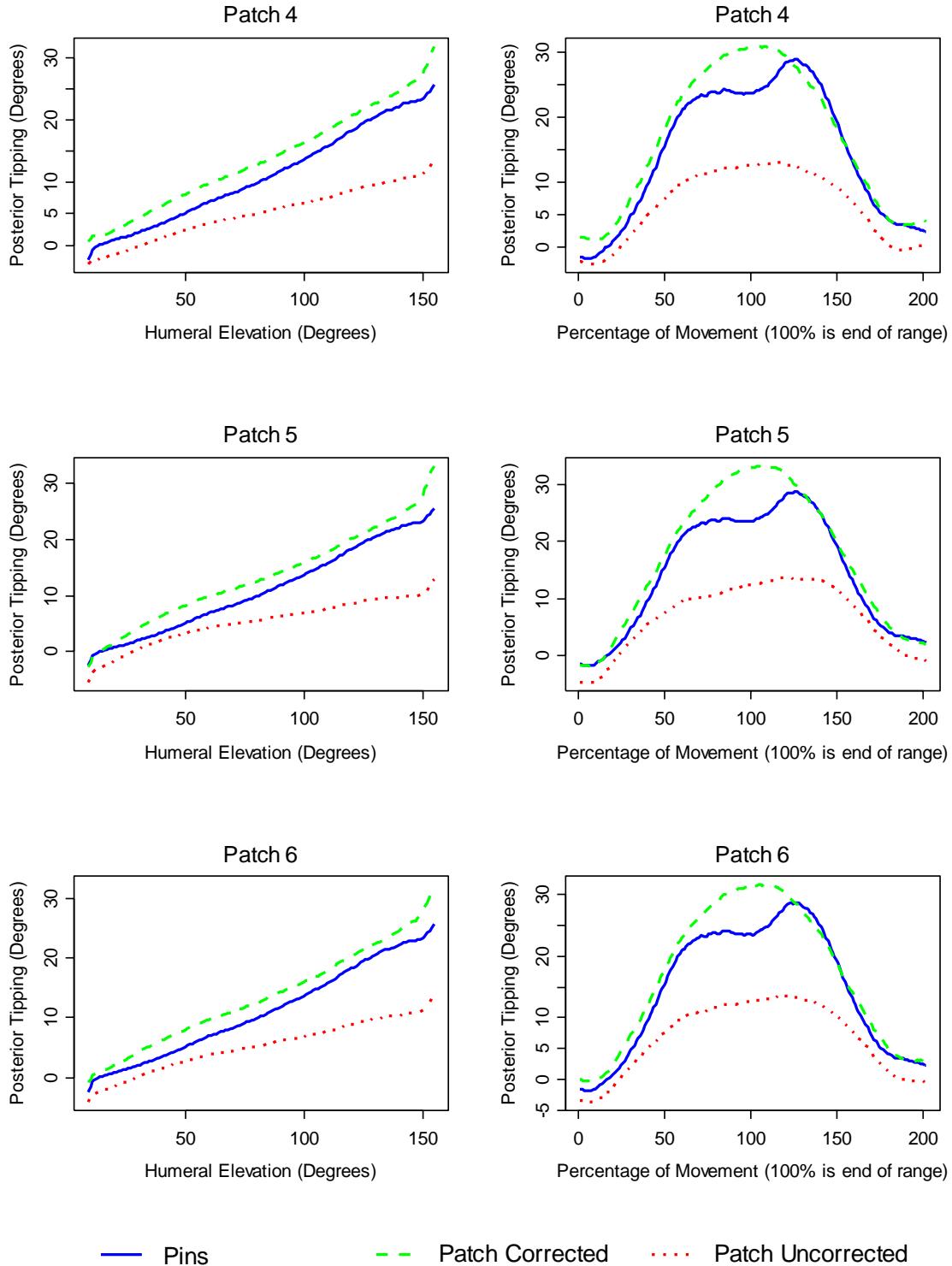
# Abduction: Pins vs. Patches Subject3

## Posterior Tipping



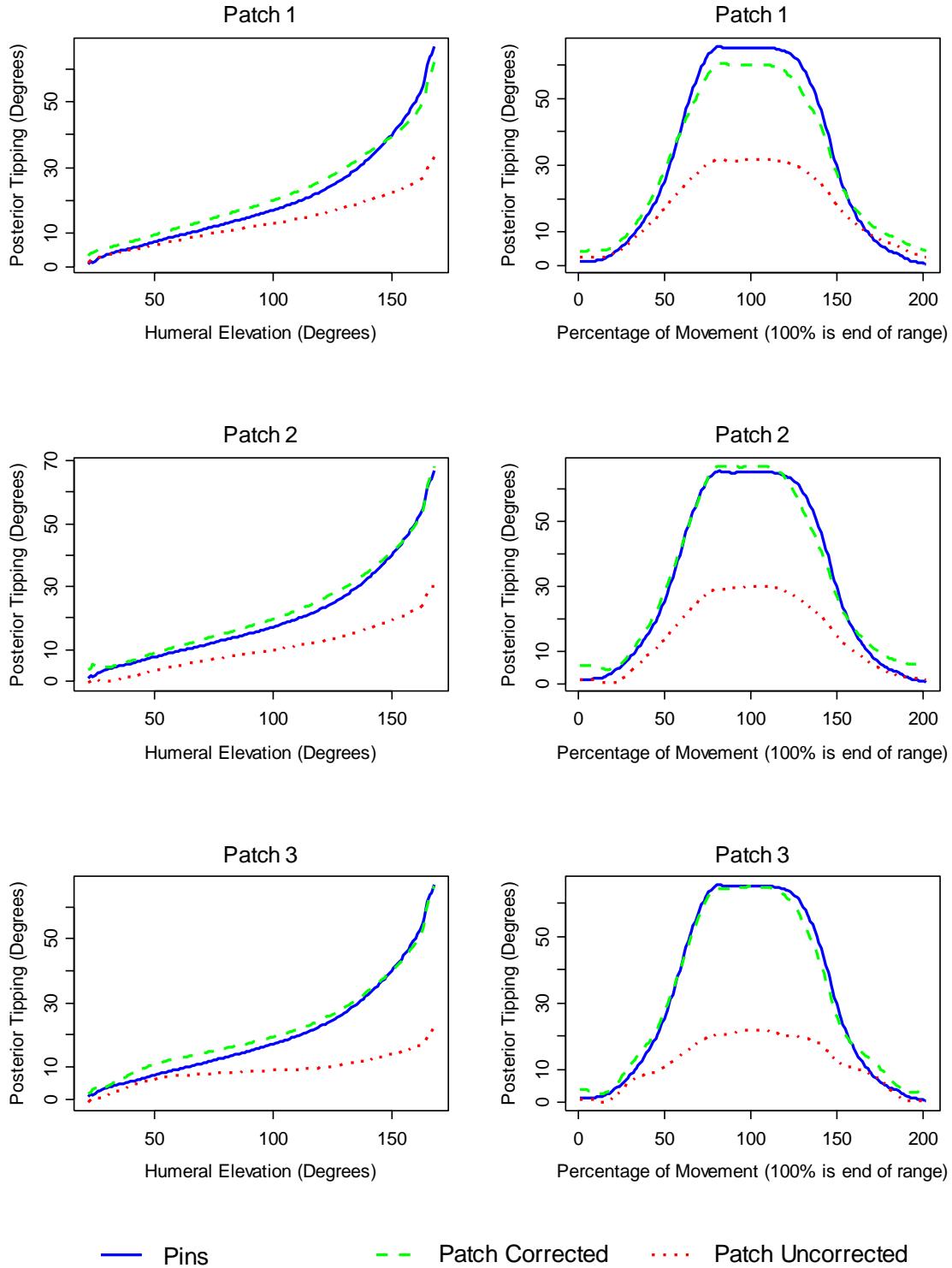
# Abduction: Pins vs. Patches Subject3

## Posterior Tipping



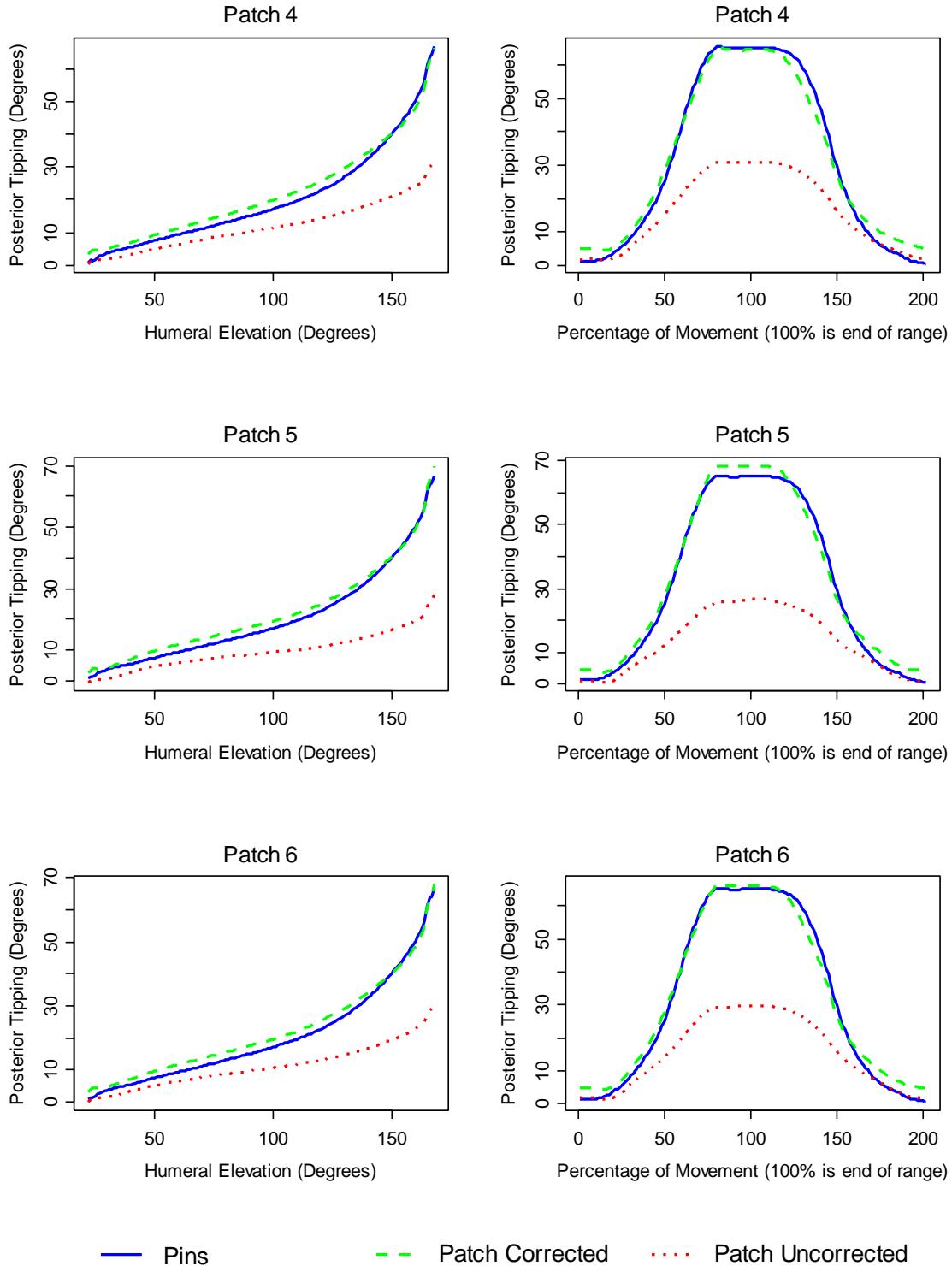
# Abduction: Pins vs. Patches Subject4

## Posterior Tipping

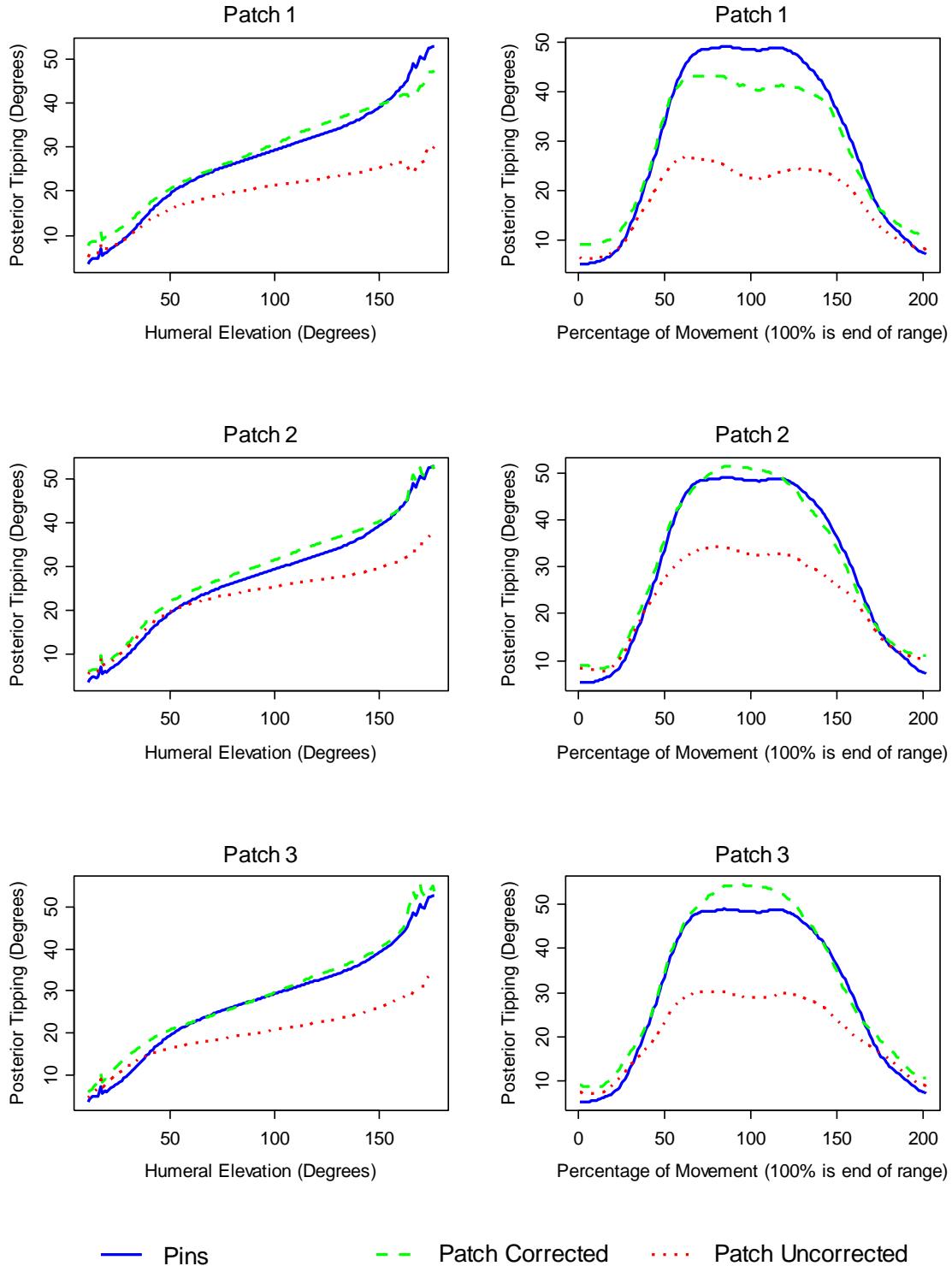


## Abduction: Pins vs. Patches Subject4

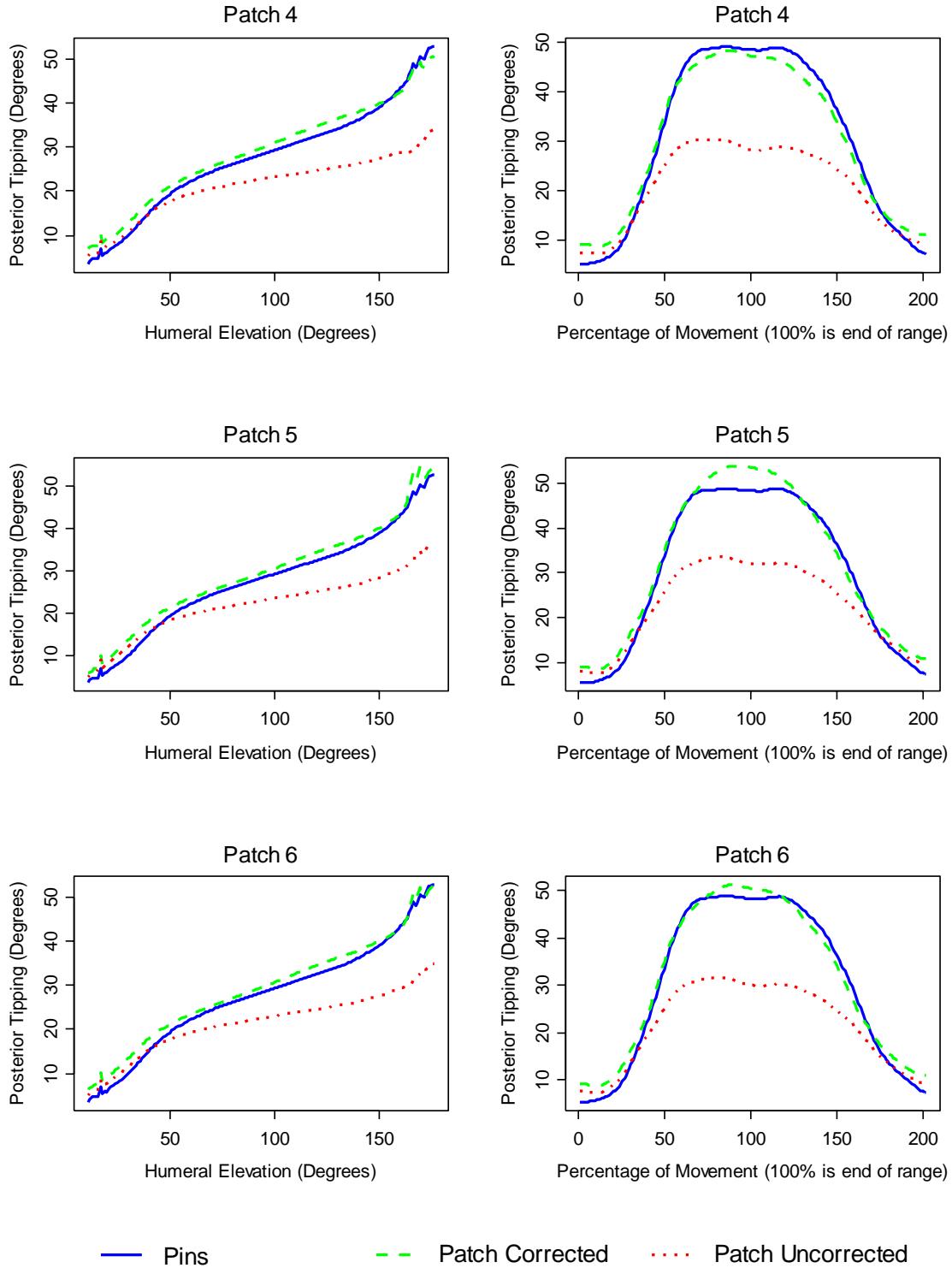
### Posterior Tipping



## Abduction: Pins vs. Patches Subject5 Posterior Tipping

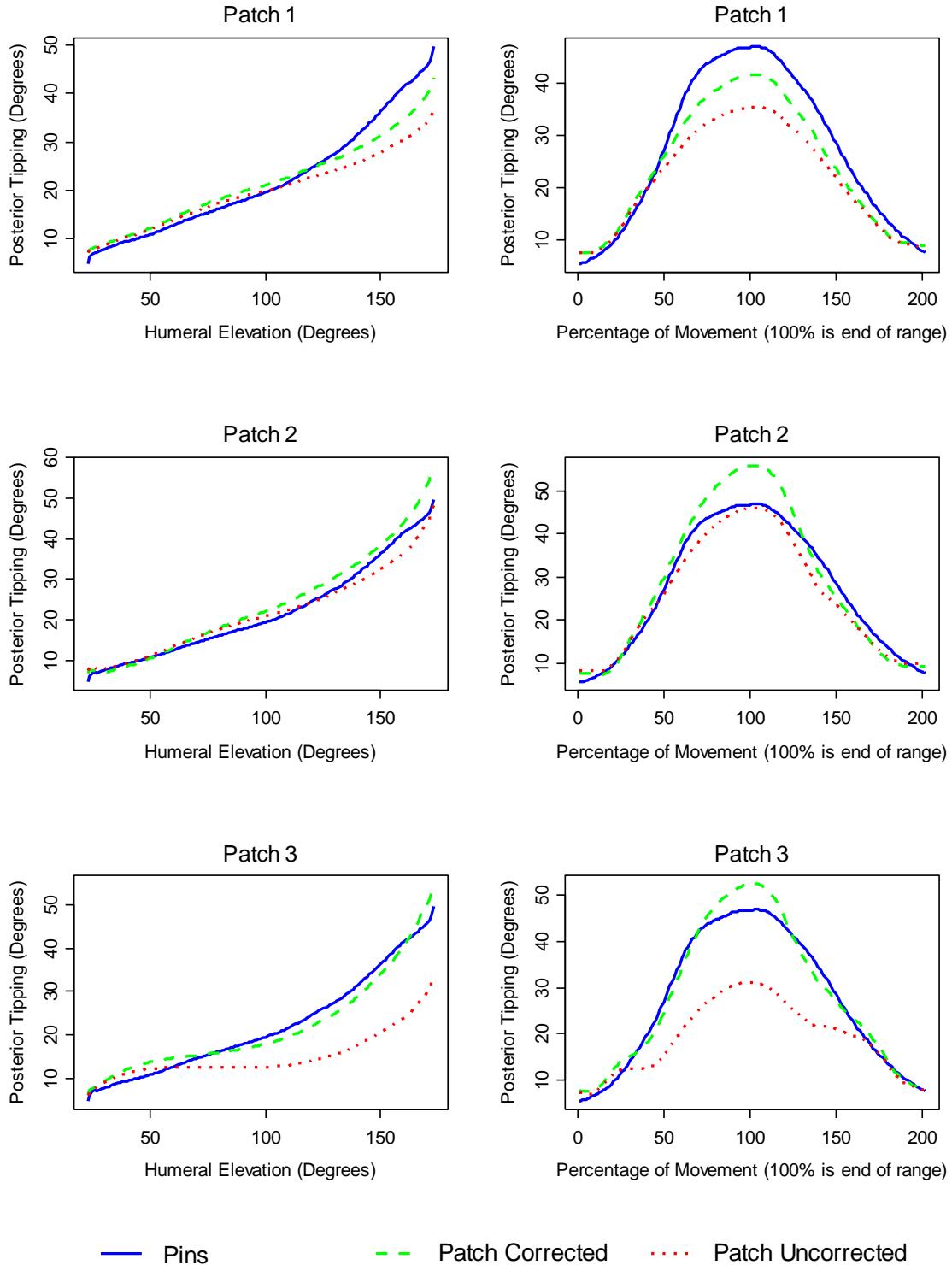


## Abduction: Pins vs. Patches Subject5 Posterior Tipping



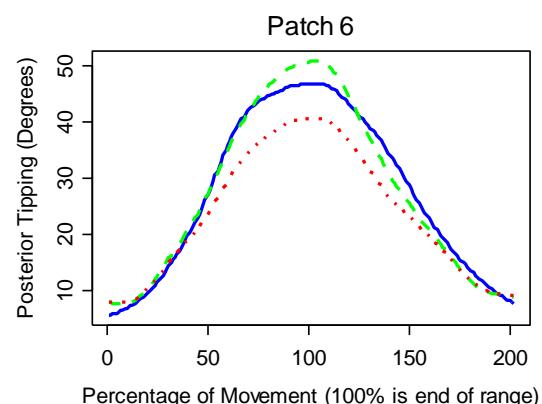
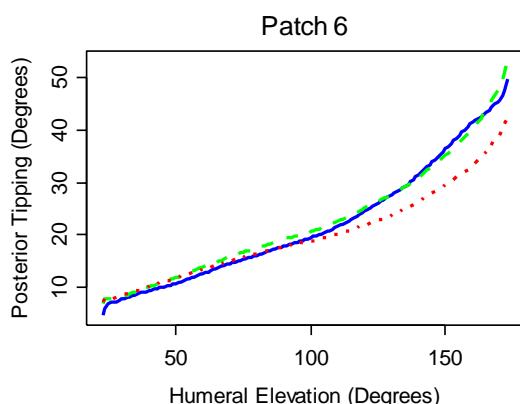
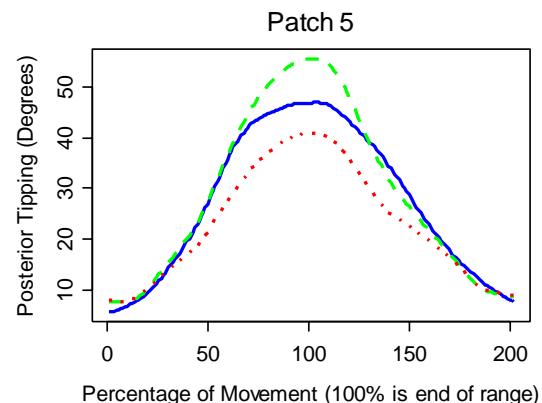
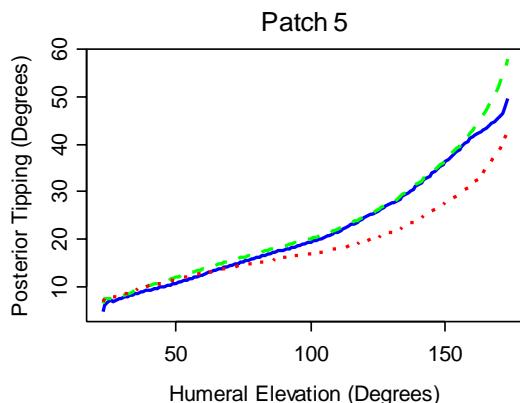
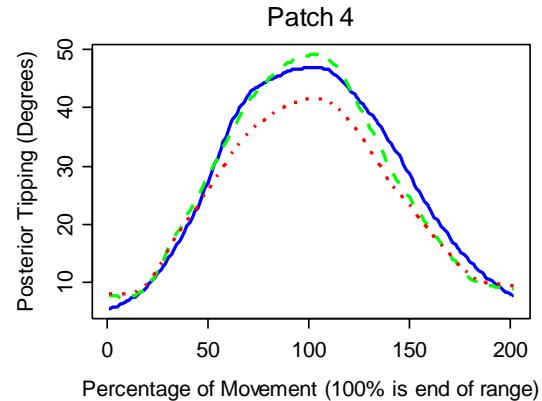
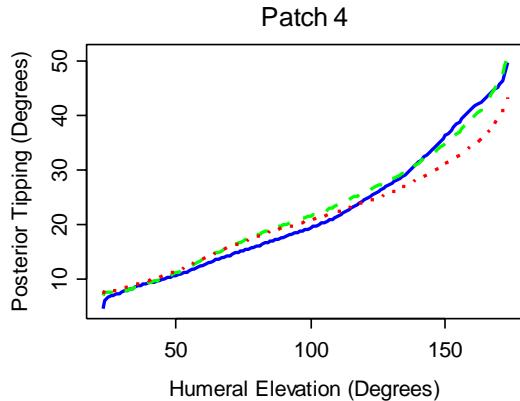
# Abduction: Pins vs. Patches Subject6

## Posterior Tipping



## Abduction: Pins vs. Patches Subject6

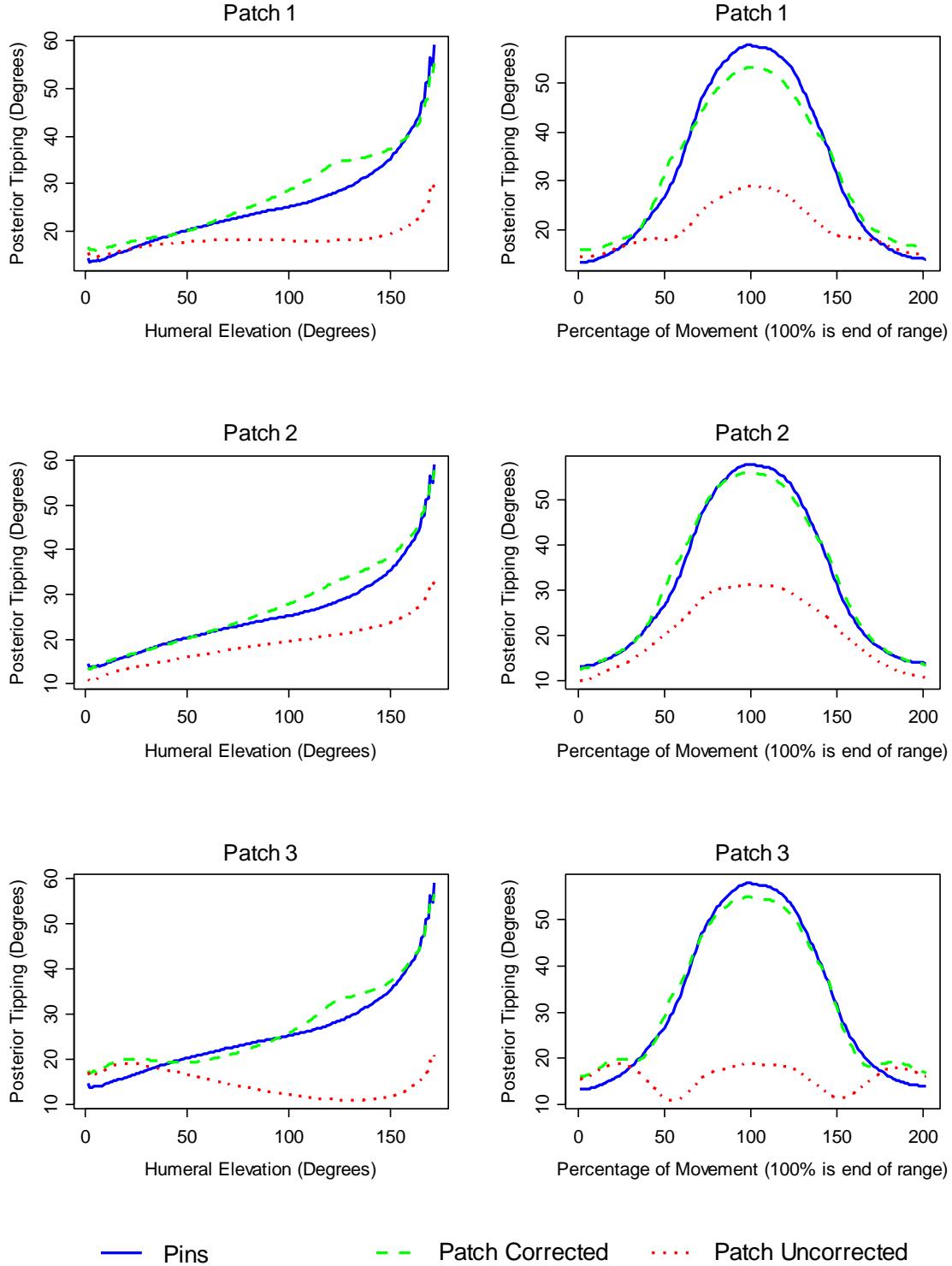
### Posterior Tipping



— Pins      - - - Patch Corrected      ... Patch Uncorrected

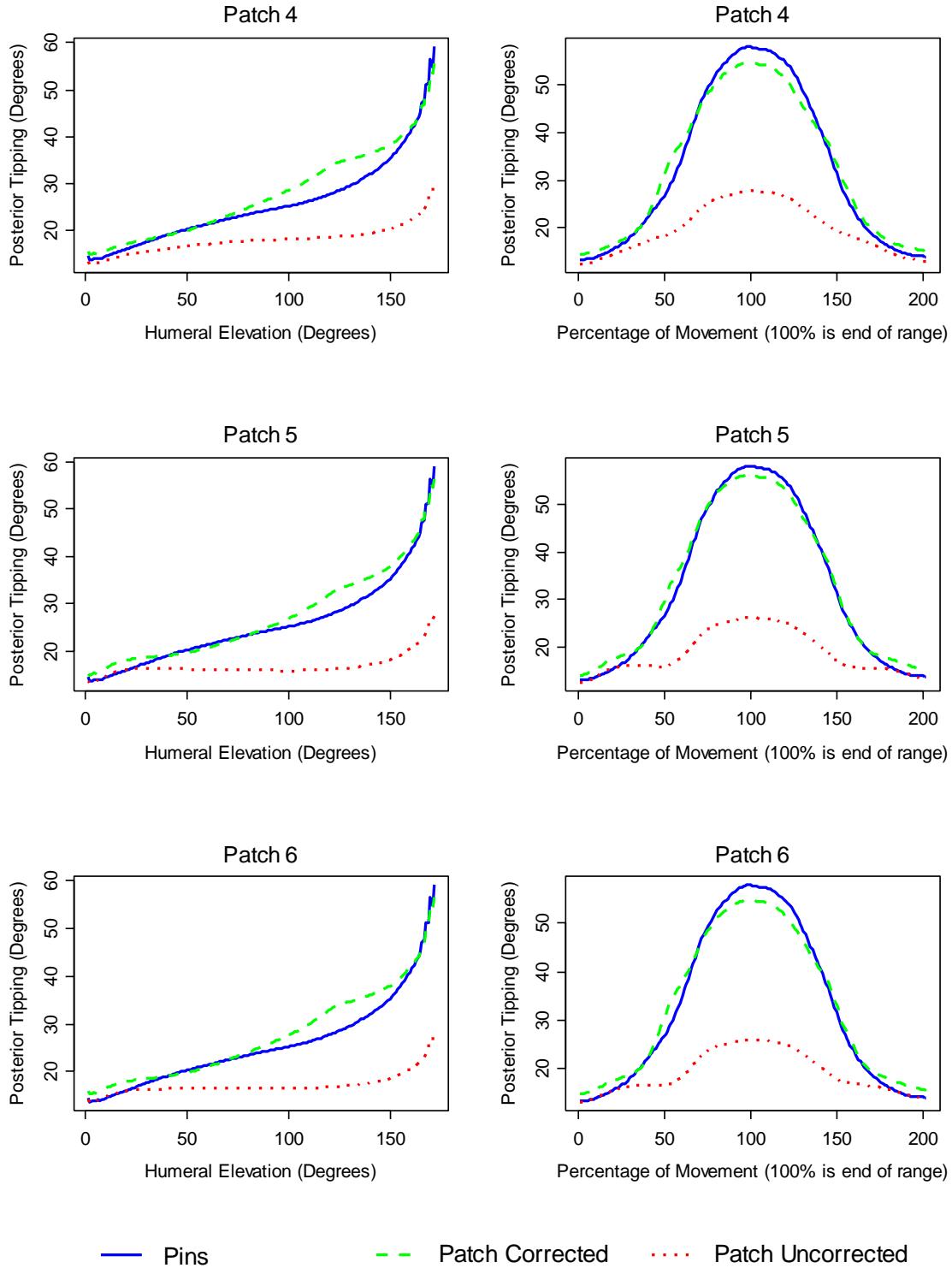
# Abduction: Pins vs. Patches Subject7

## Posterior Tipping



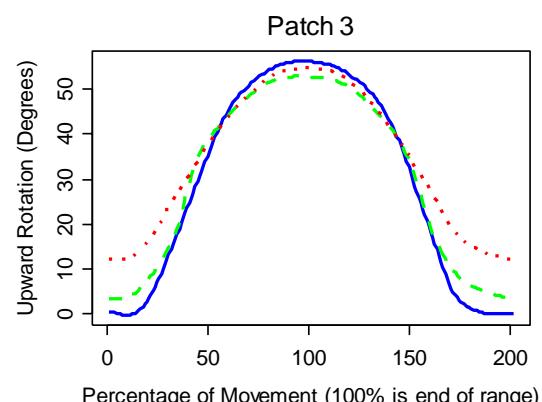
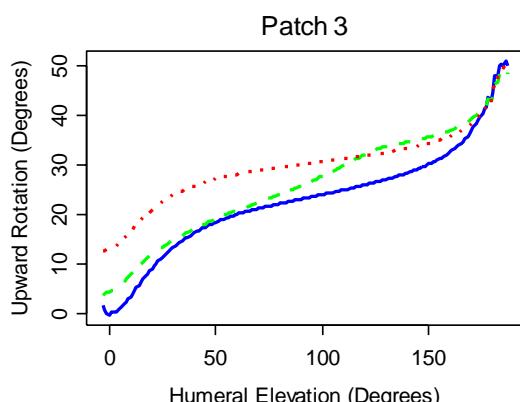
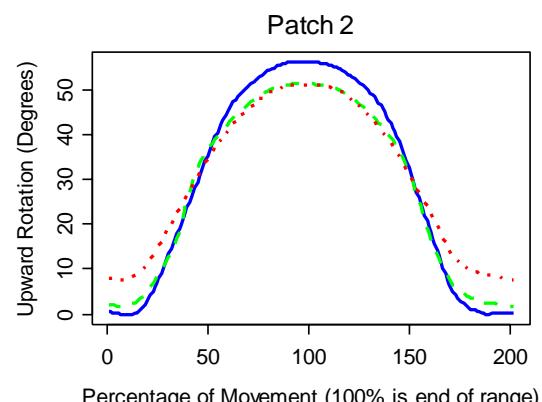
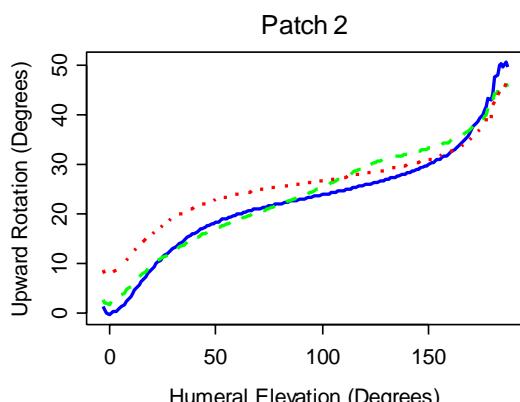
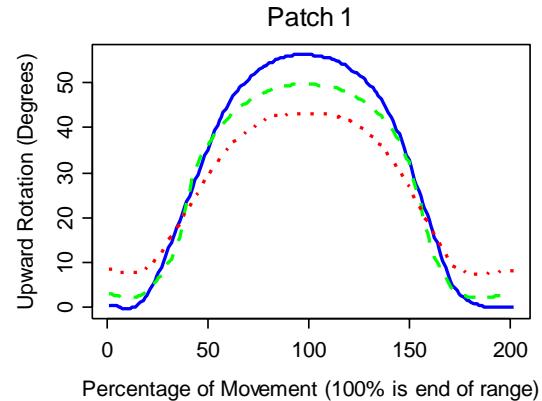
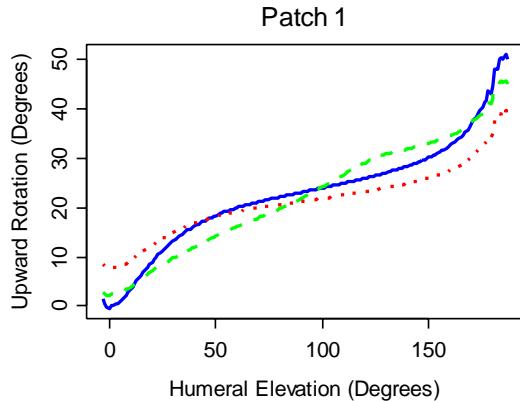
# Abduction: Pins vs. Patches Subject7

## Posterior Tipping



# Abduction: Pins vs. Patches Subject1

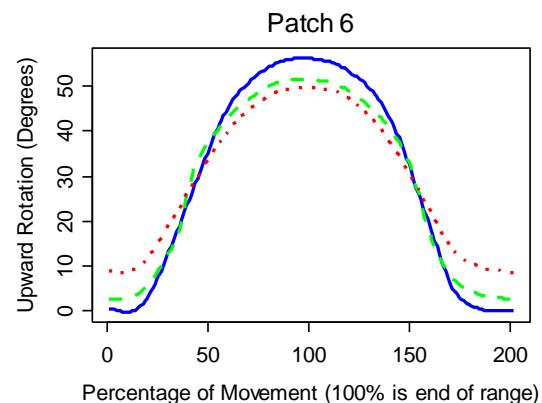
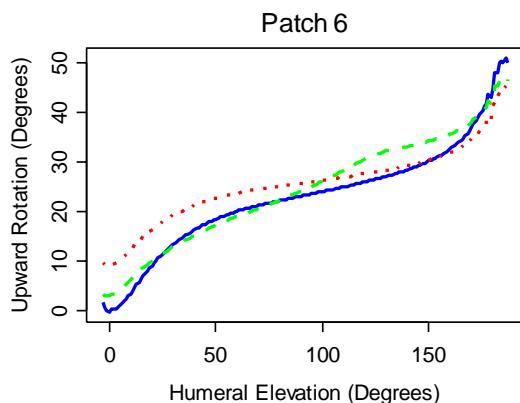
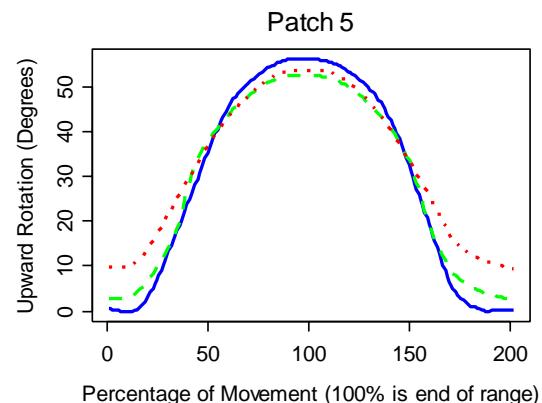
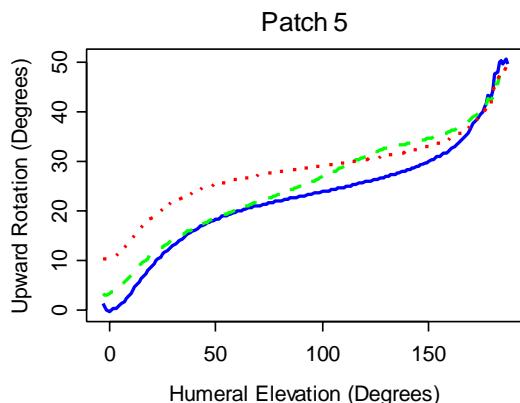
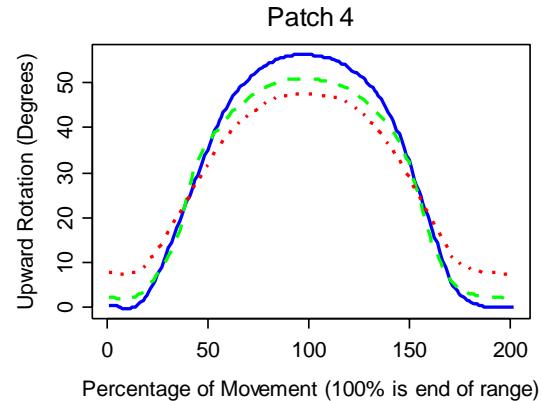
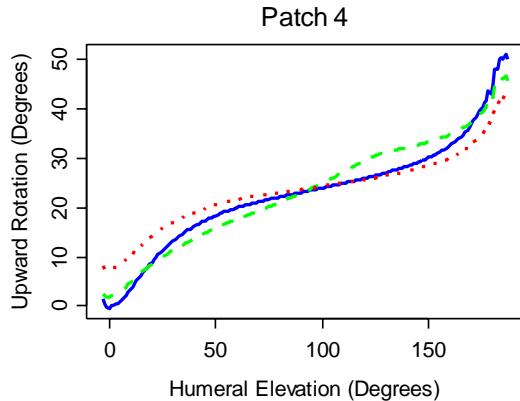
## Upward Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

# Abduction: Pins vs. Patches Subject1

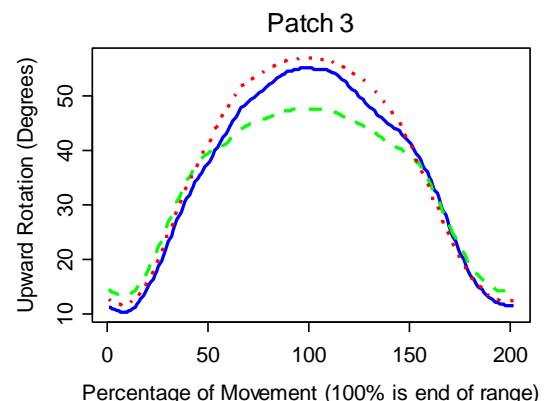
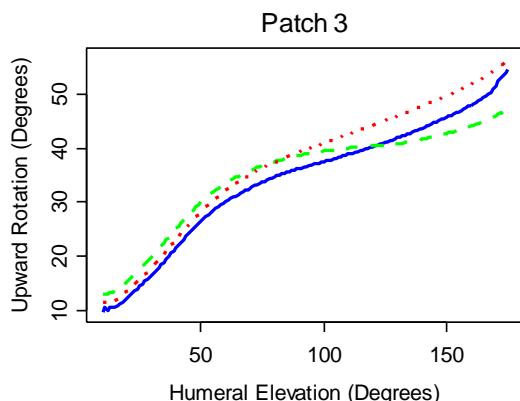
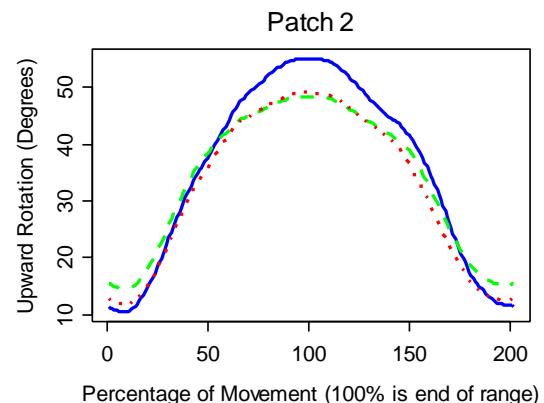
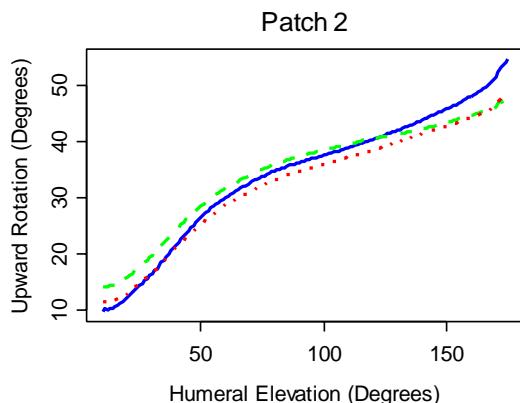
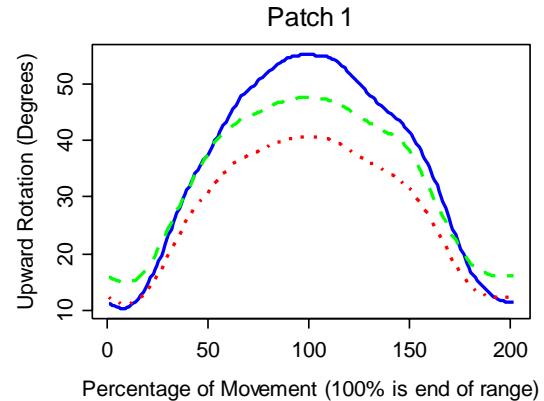
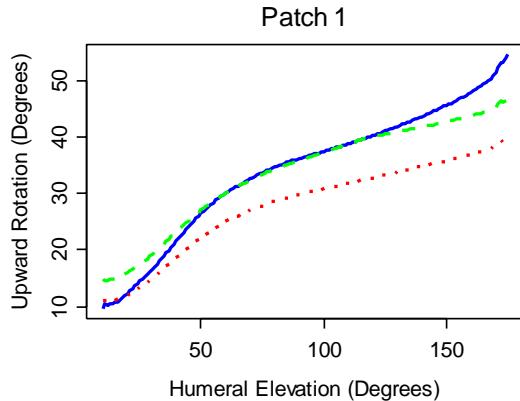
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

## Abduction: Pins vs. Patches Subject2

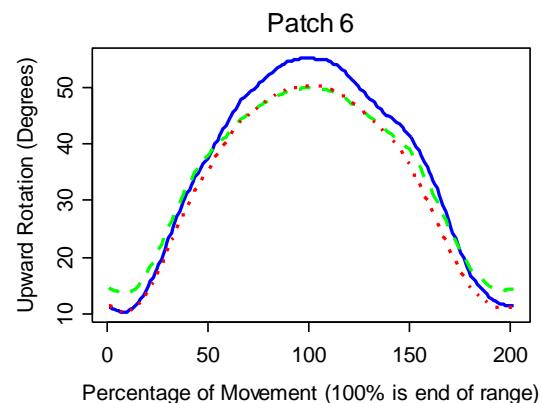
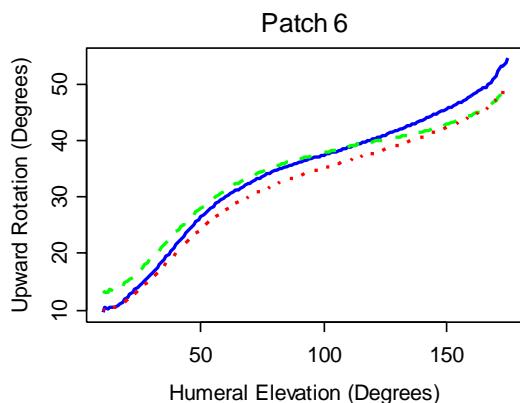
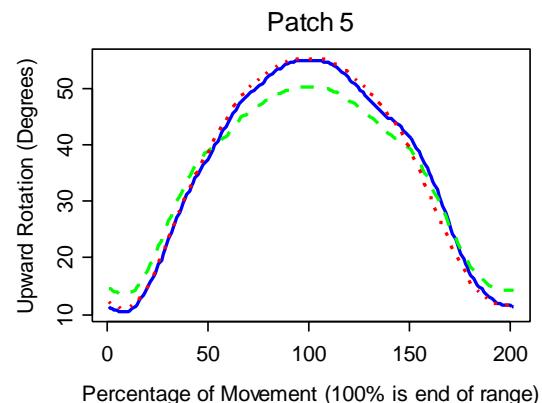
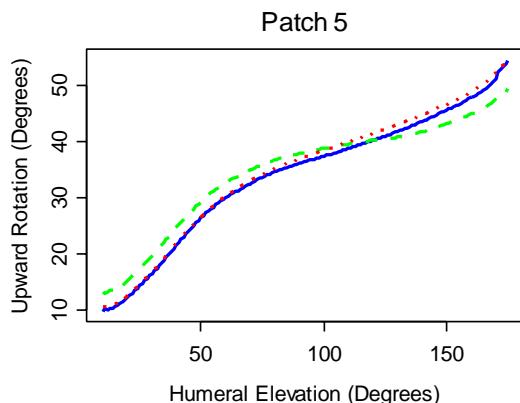
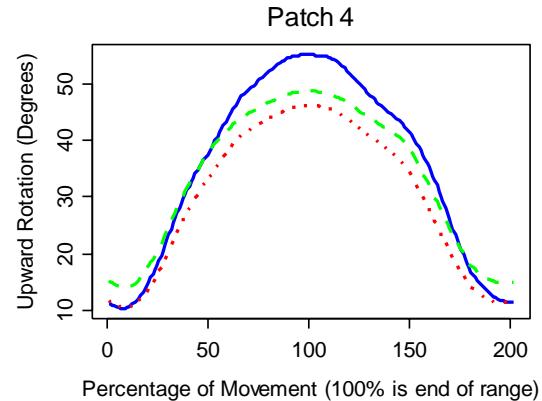
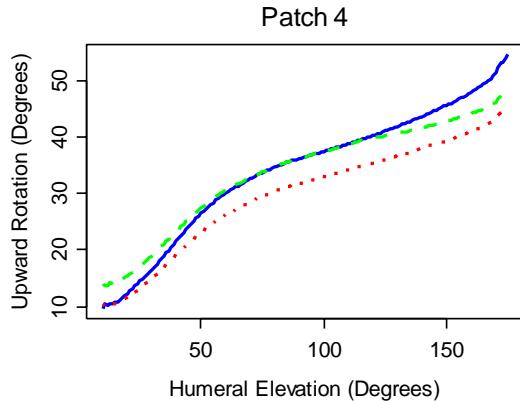
### Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

## Abduction: Pins vs. Patches Subject2

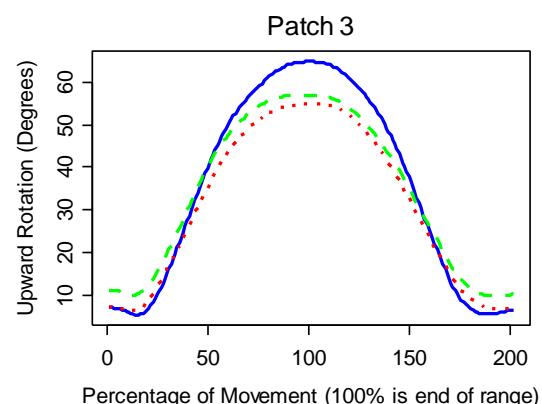
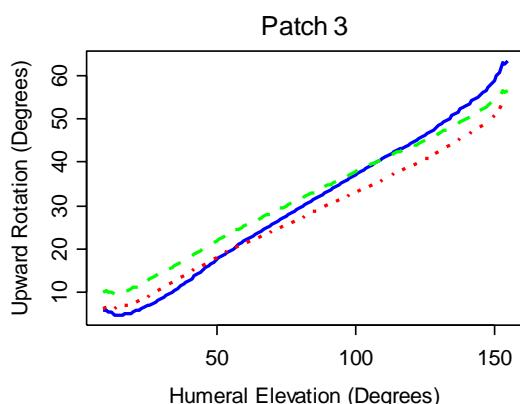
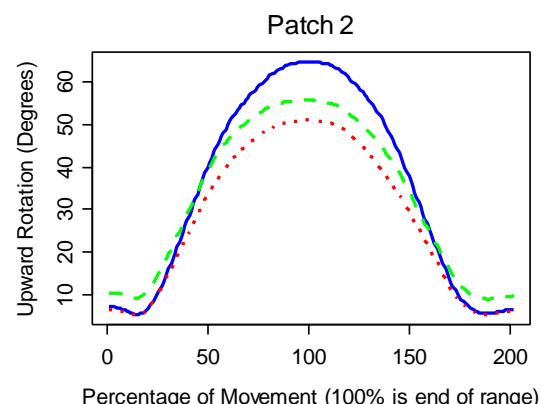
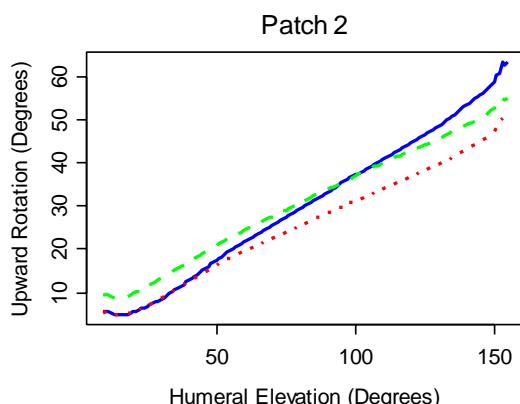
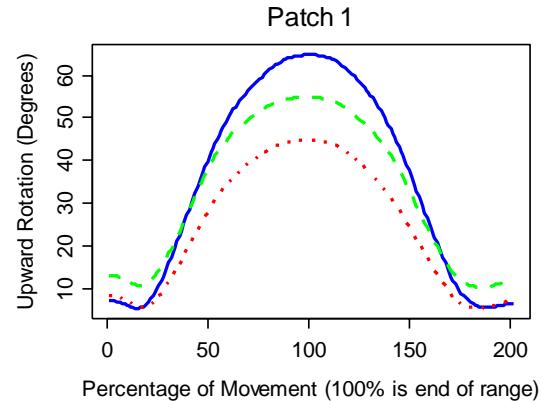
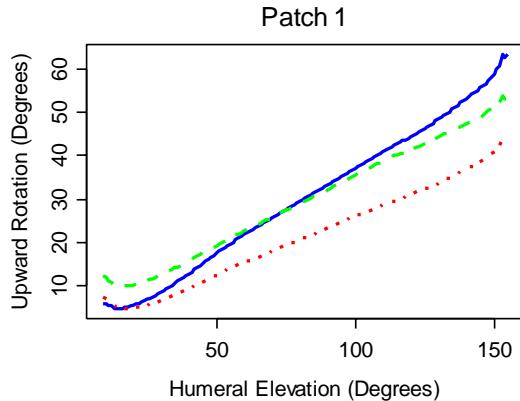
### Upward Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

# Abduction: Pins vs. Patches Subject3

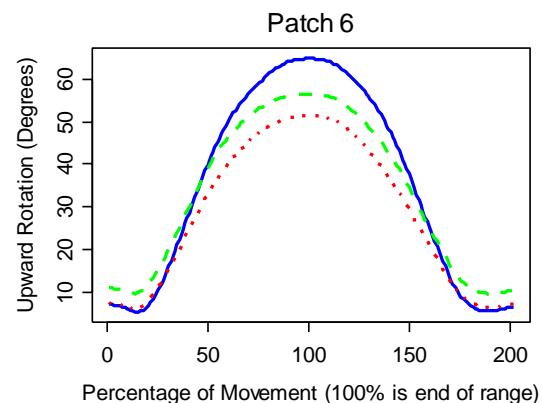
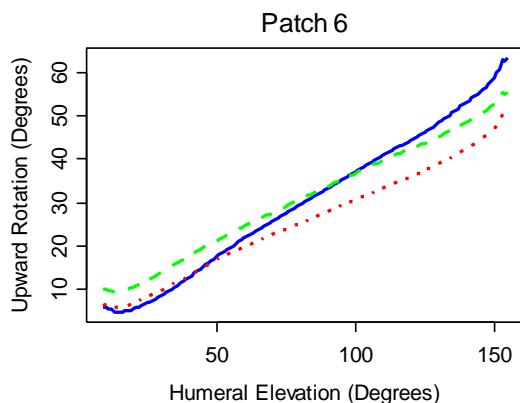
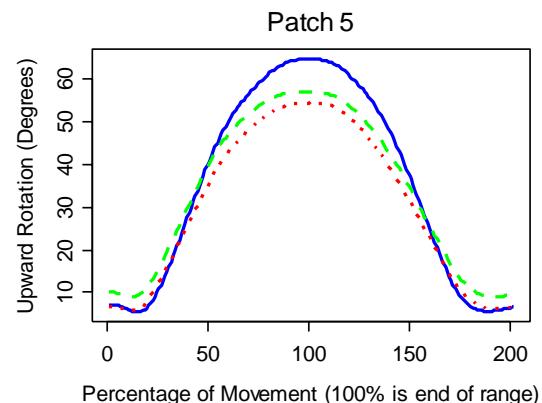
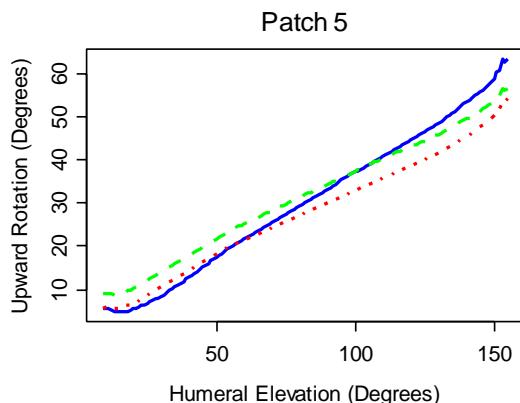
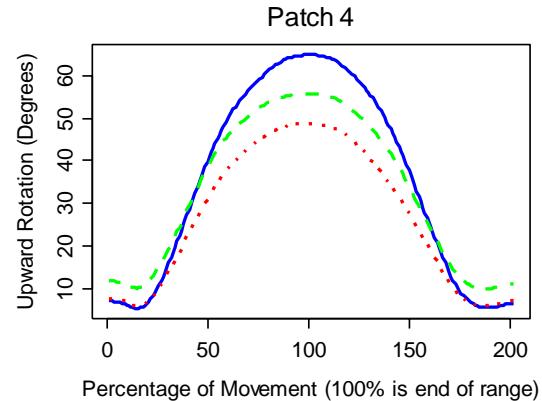
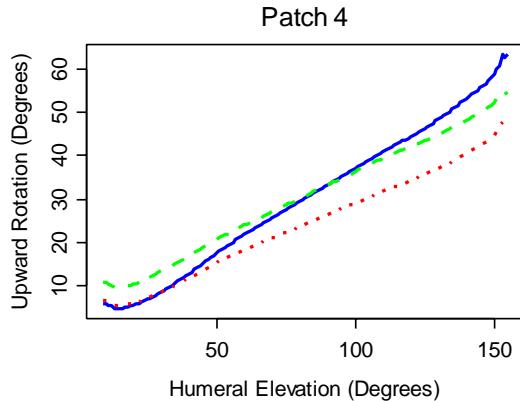
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject3

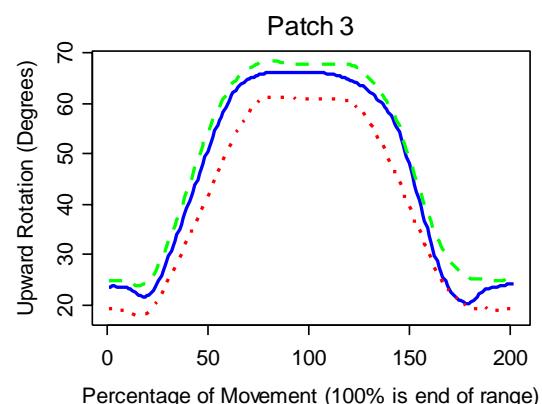
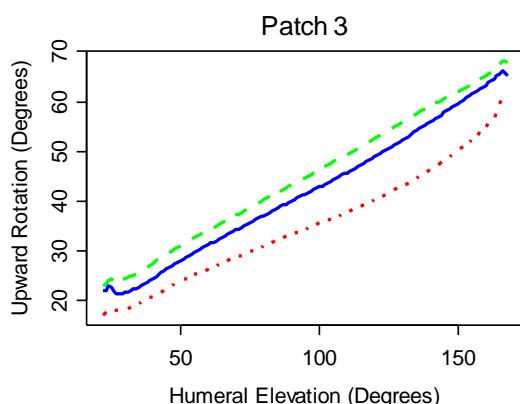
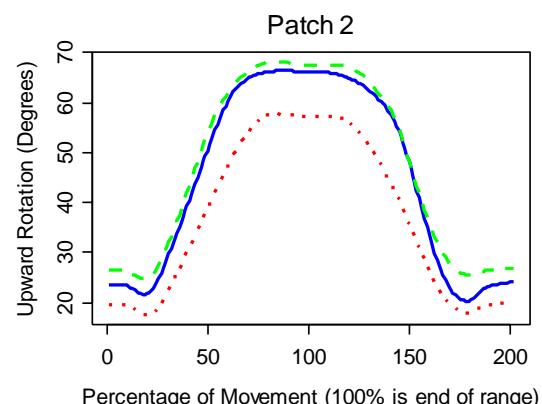
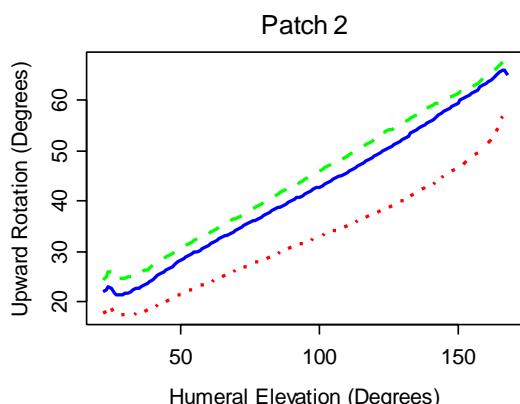
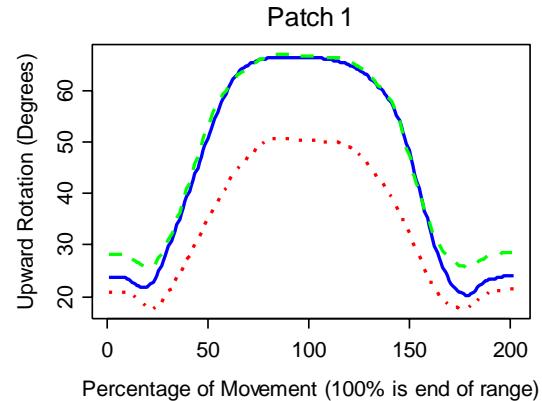
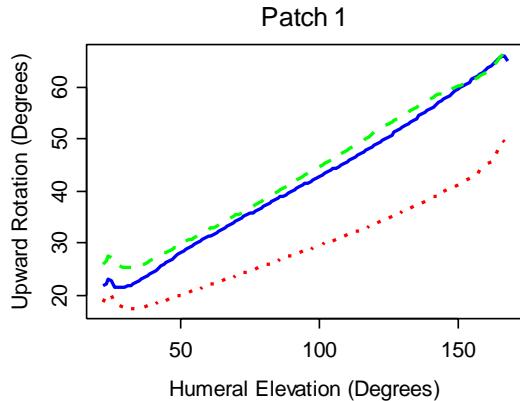
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject4

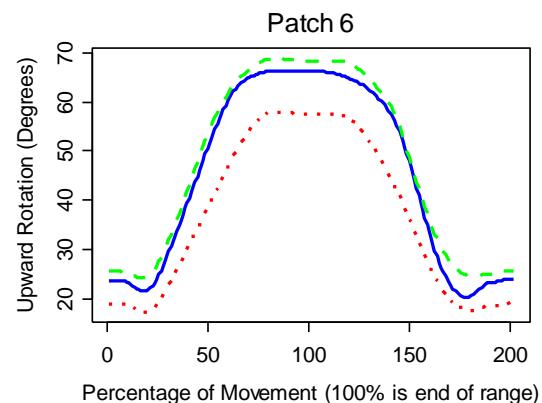
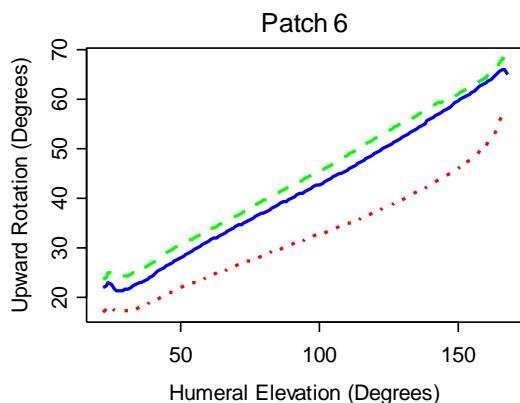
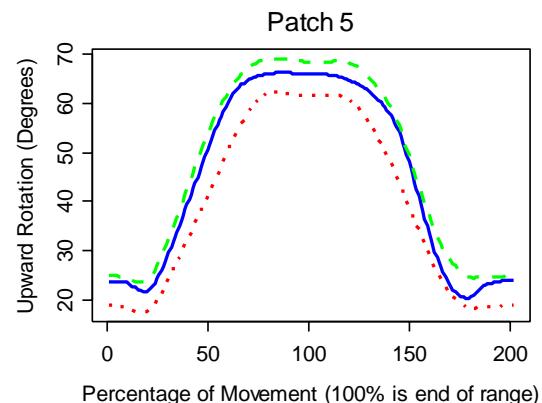
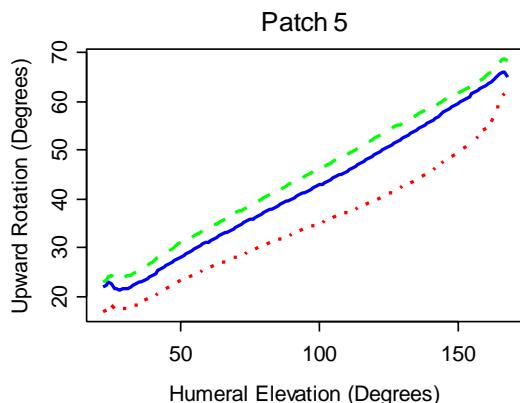
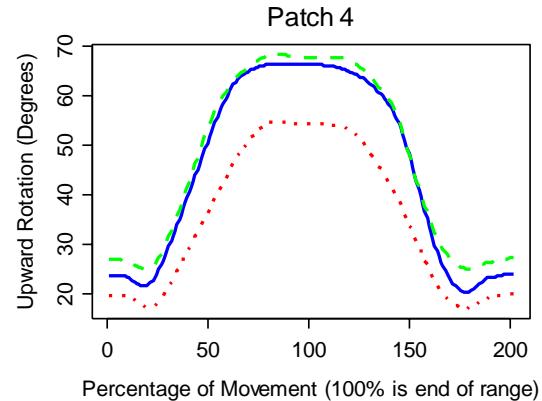
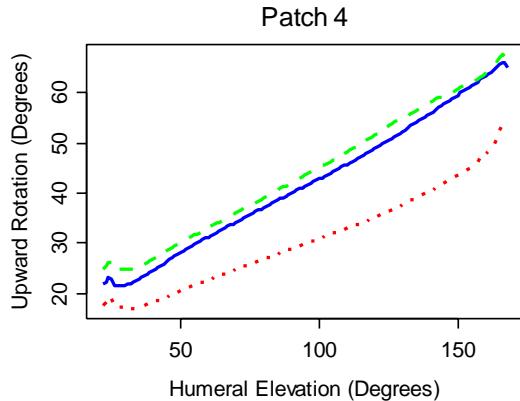
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject4

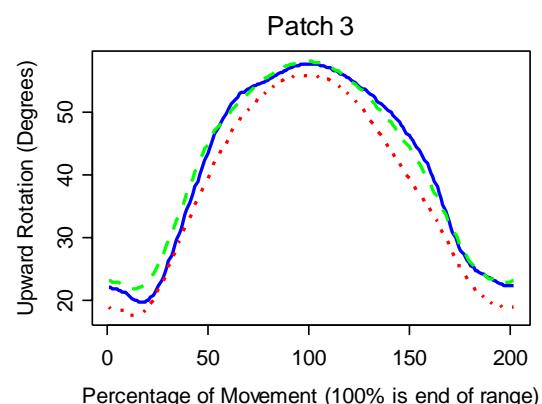
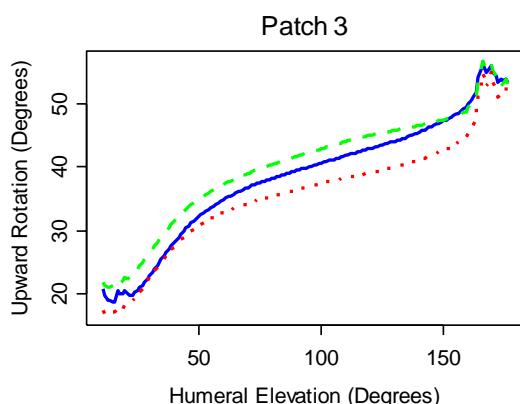
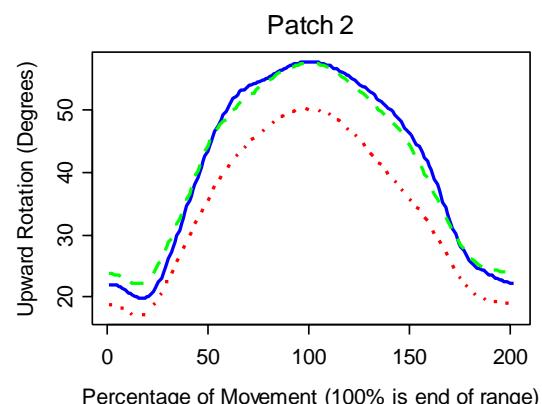
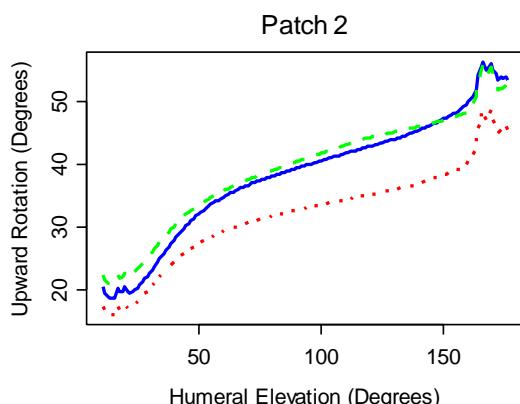
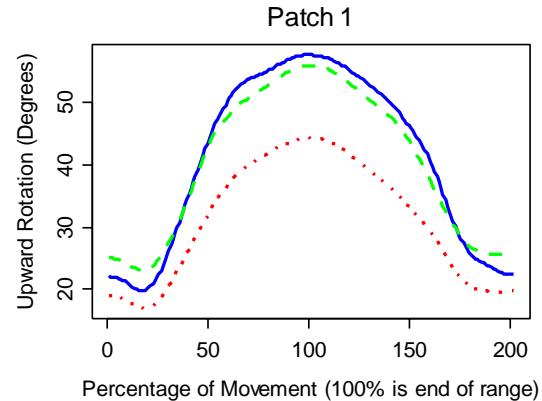
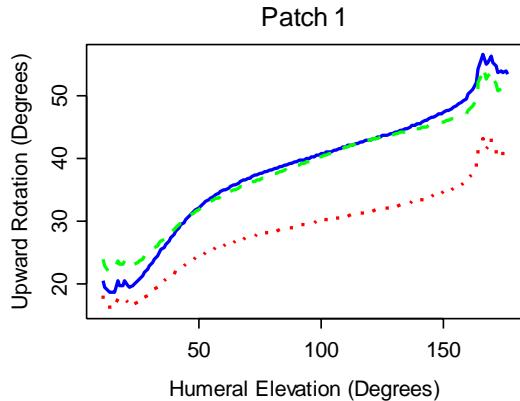
## Upward Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

# Abduction: Pins vs. Patches Subject5

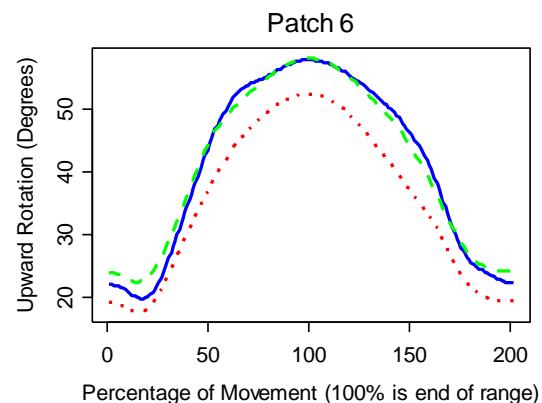
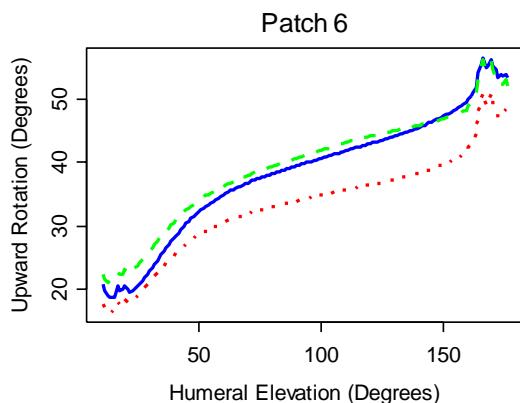
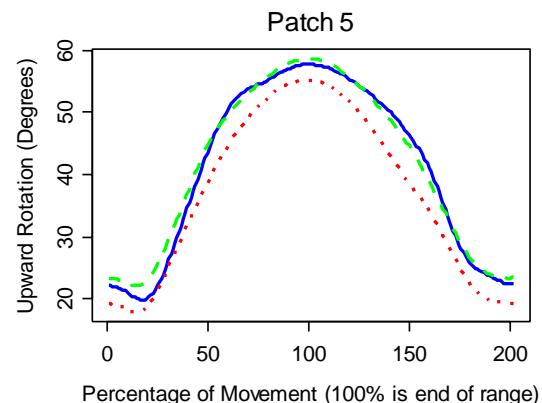
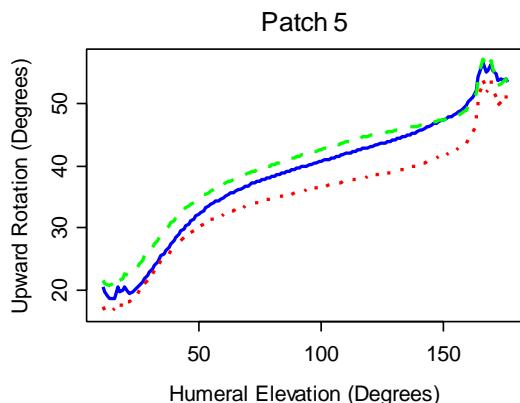
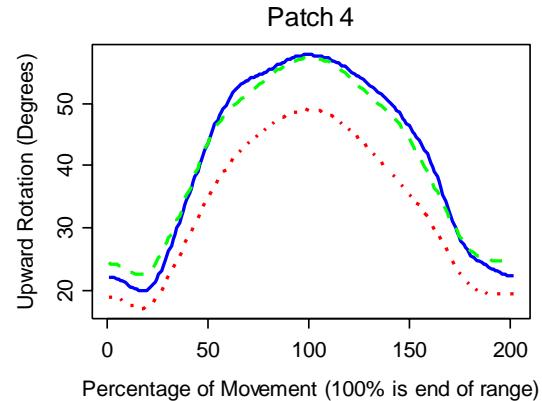
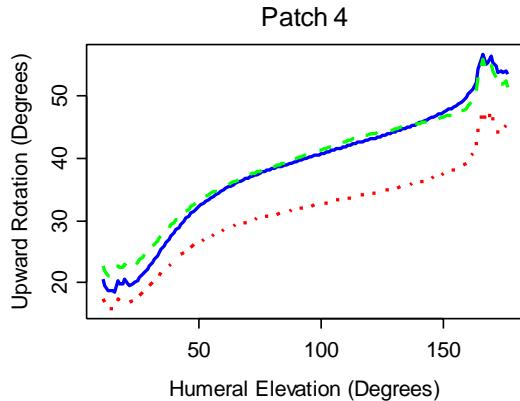
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject5

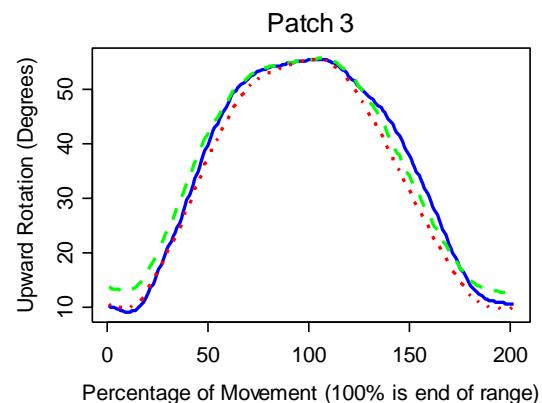
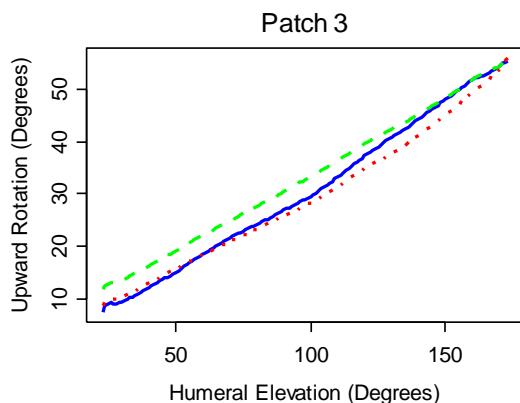
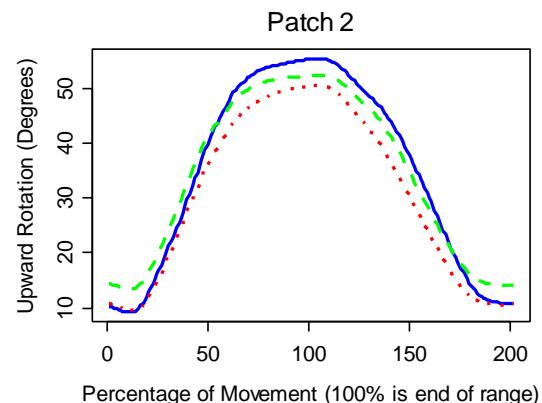
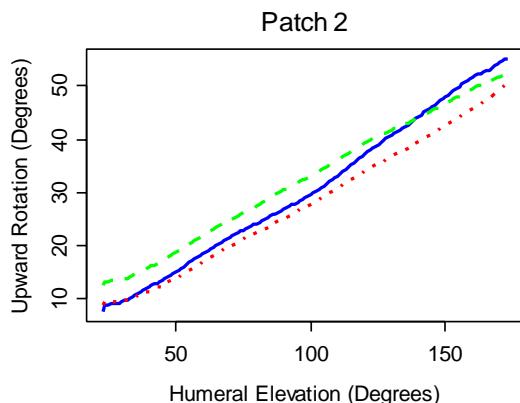
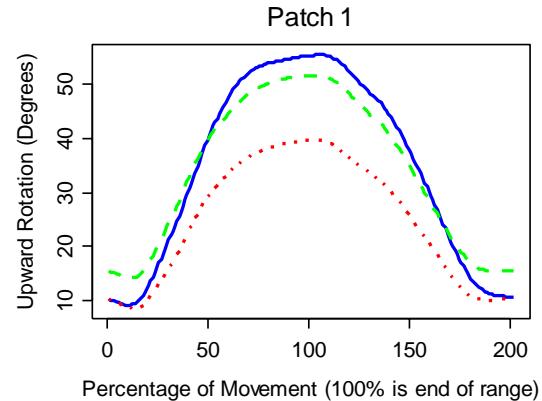
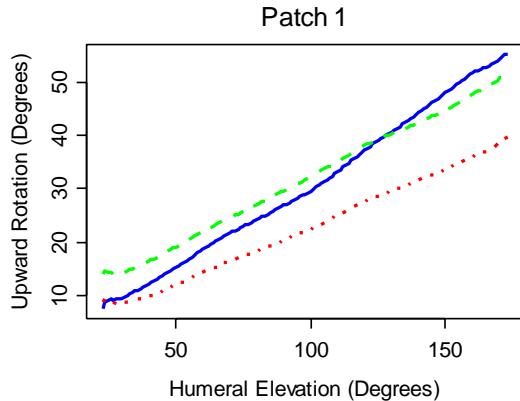
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject6

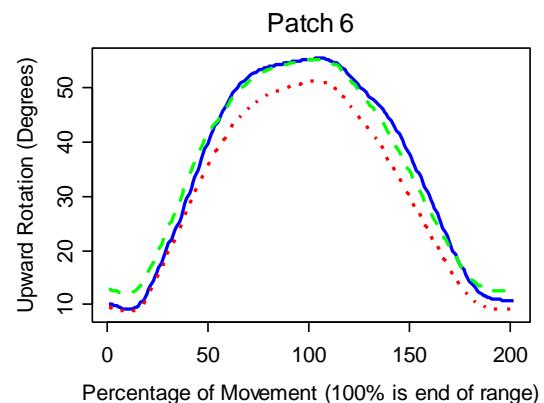
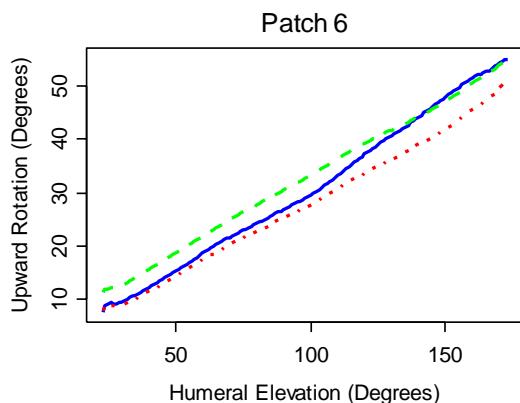
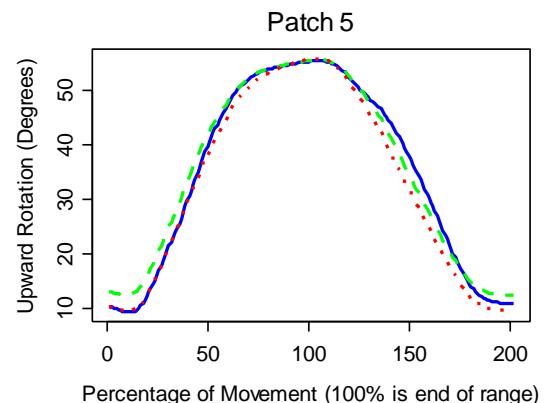
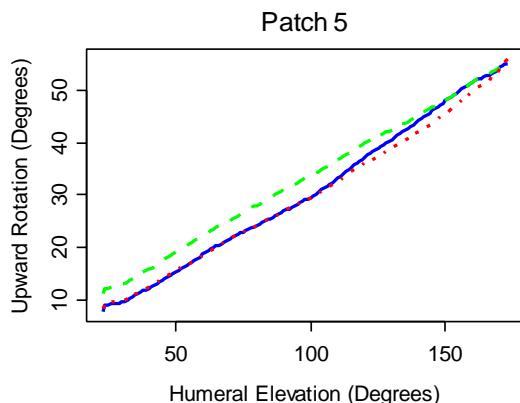
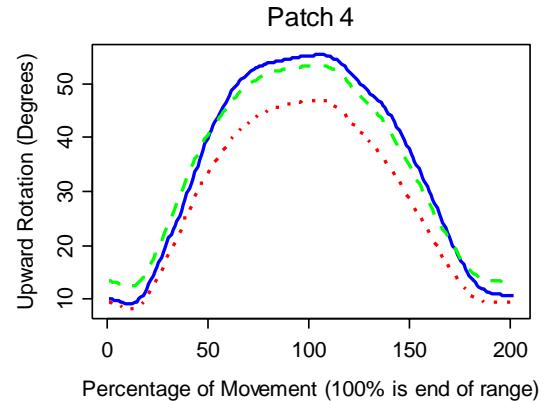
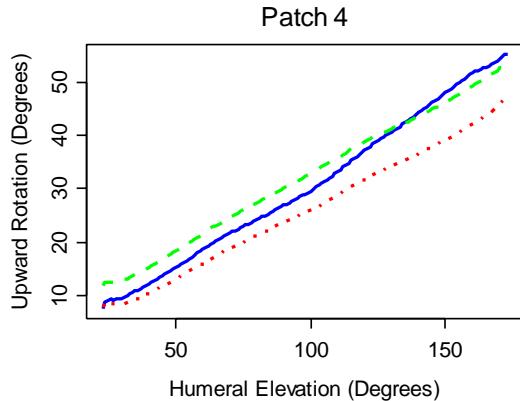
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

## Abduction: Pins vs. Patches Subject6

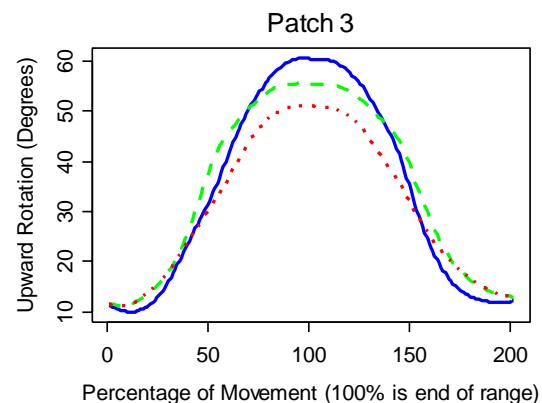
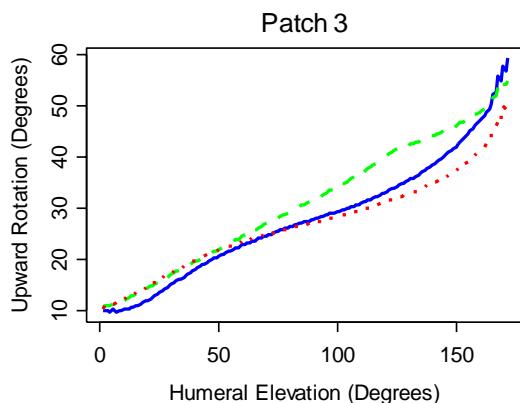
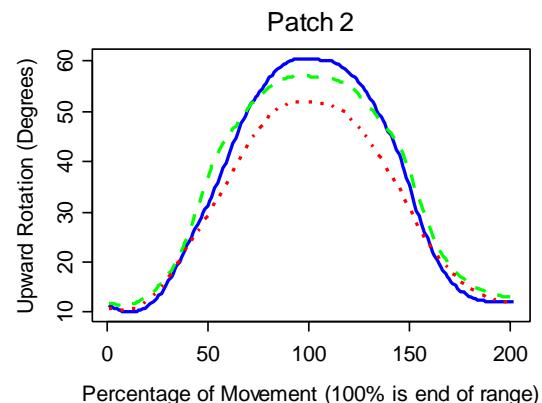
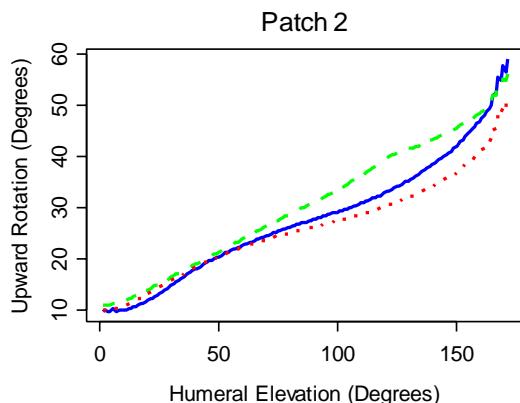
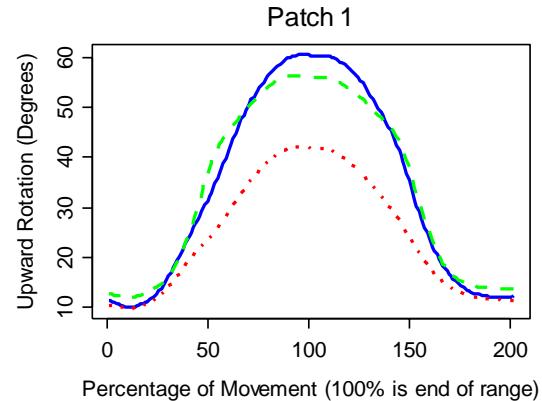
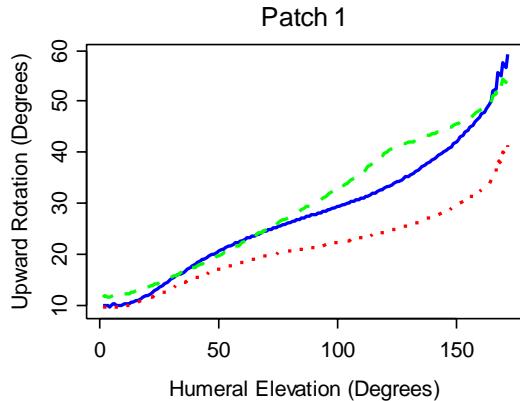
### Upward Rotation



— Pins      - Patch Corrected      . Patch Uncorrected

# Abduction: Pins vs. Patches Subject7

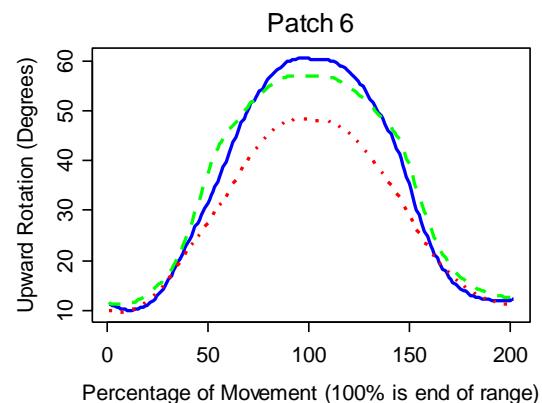
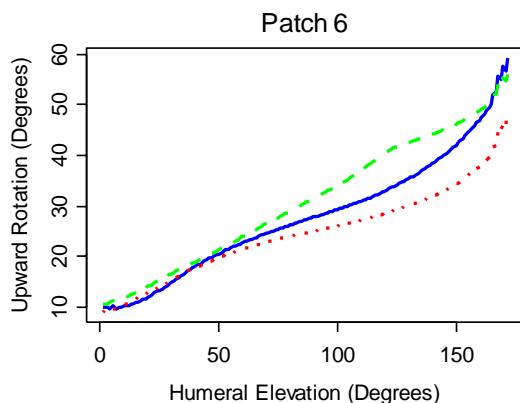
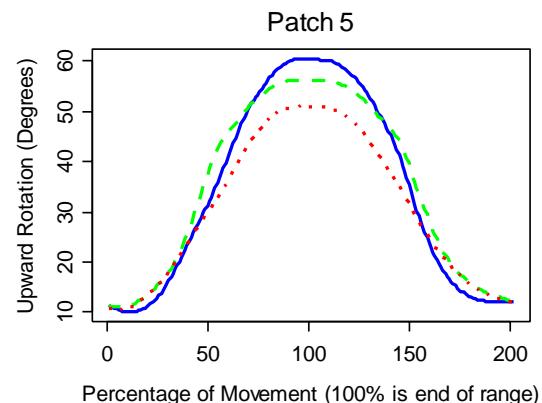
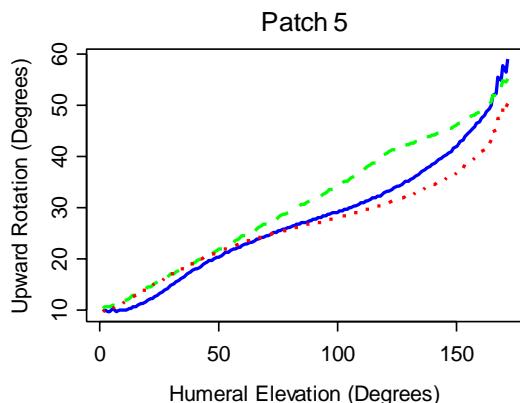
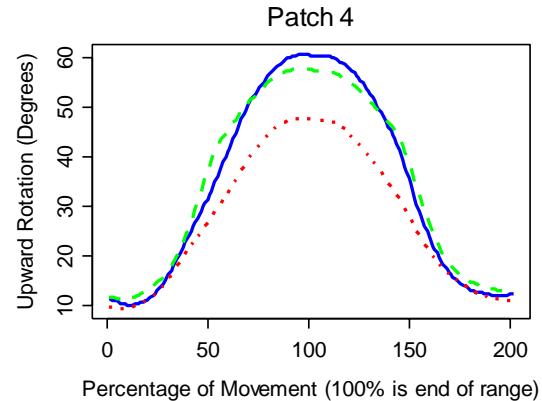
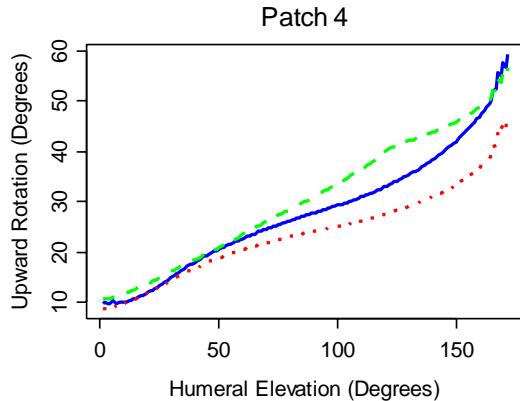
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

# Abduction: Pins vs. Patches Subject7

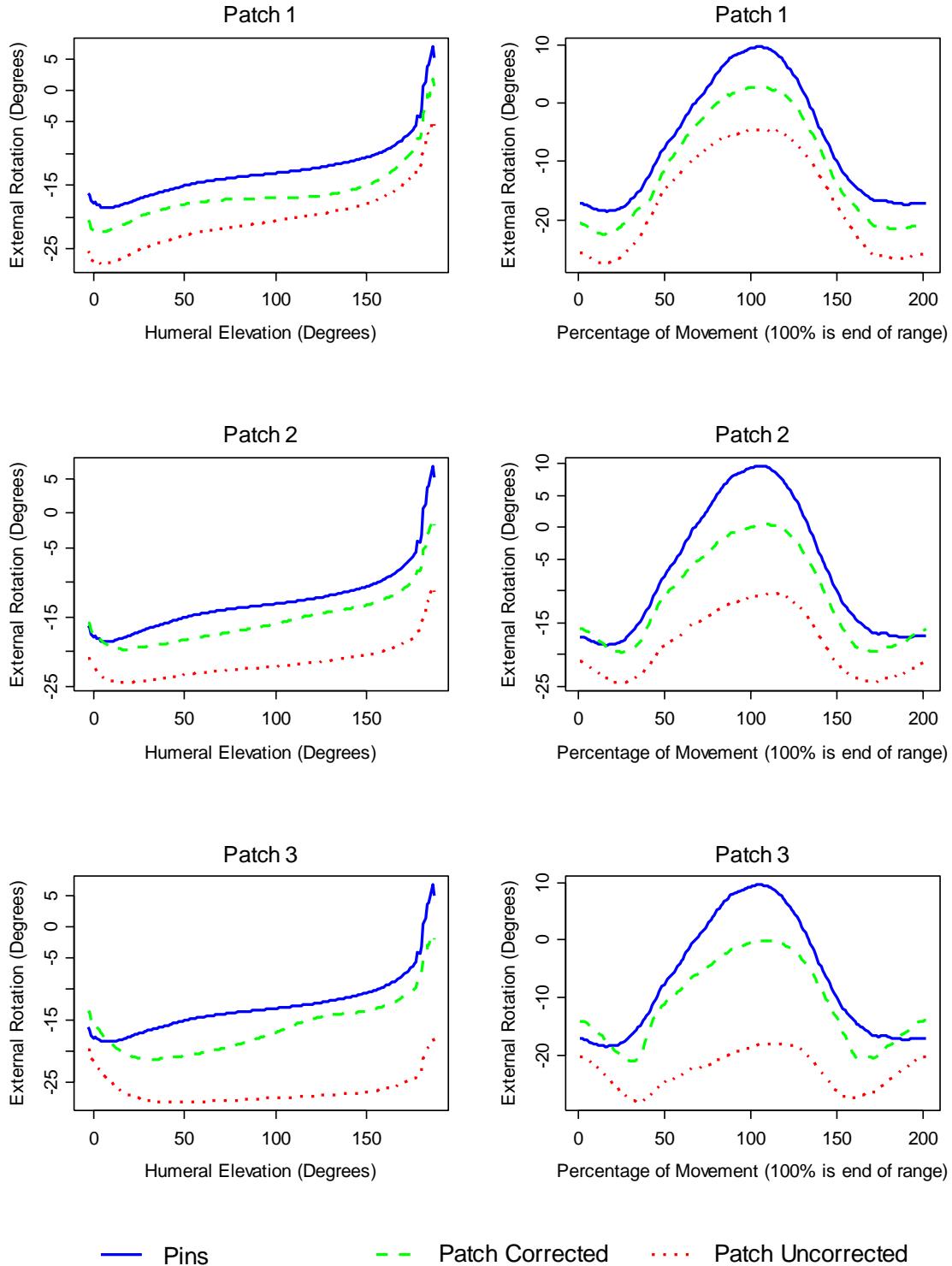
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

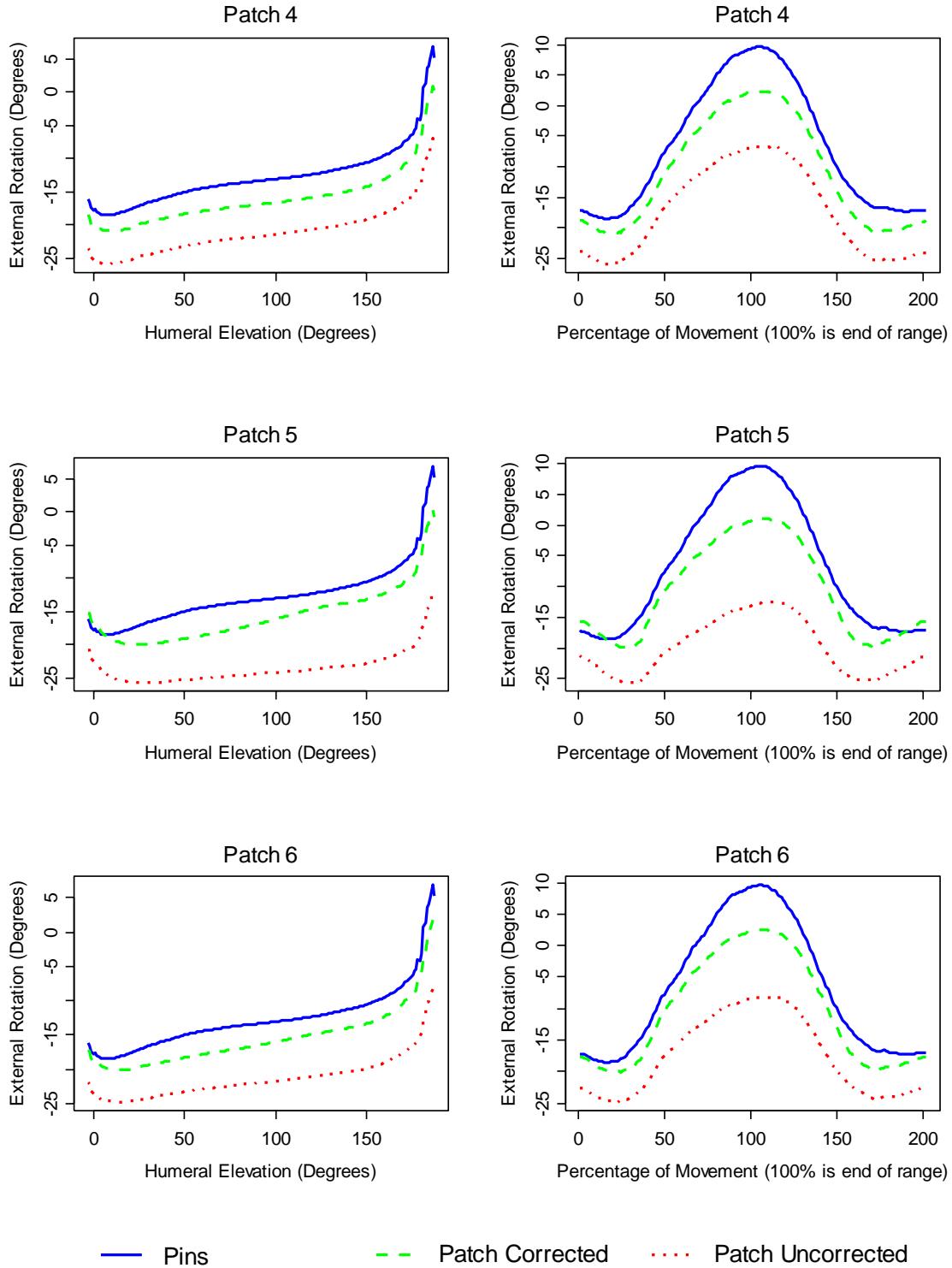
# Abduction: Pins vs. Patches Subject1

## External Rotation



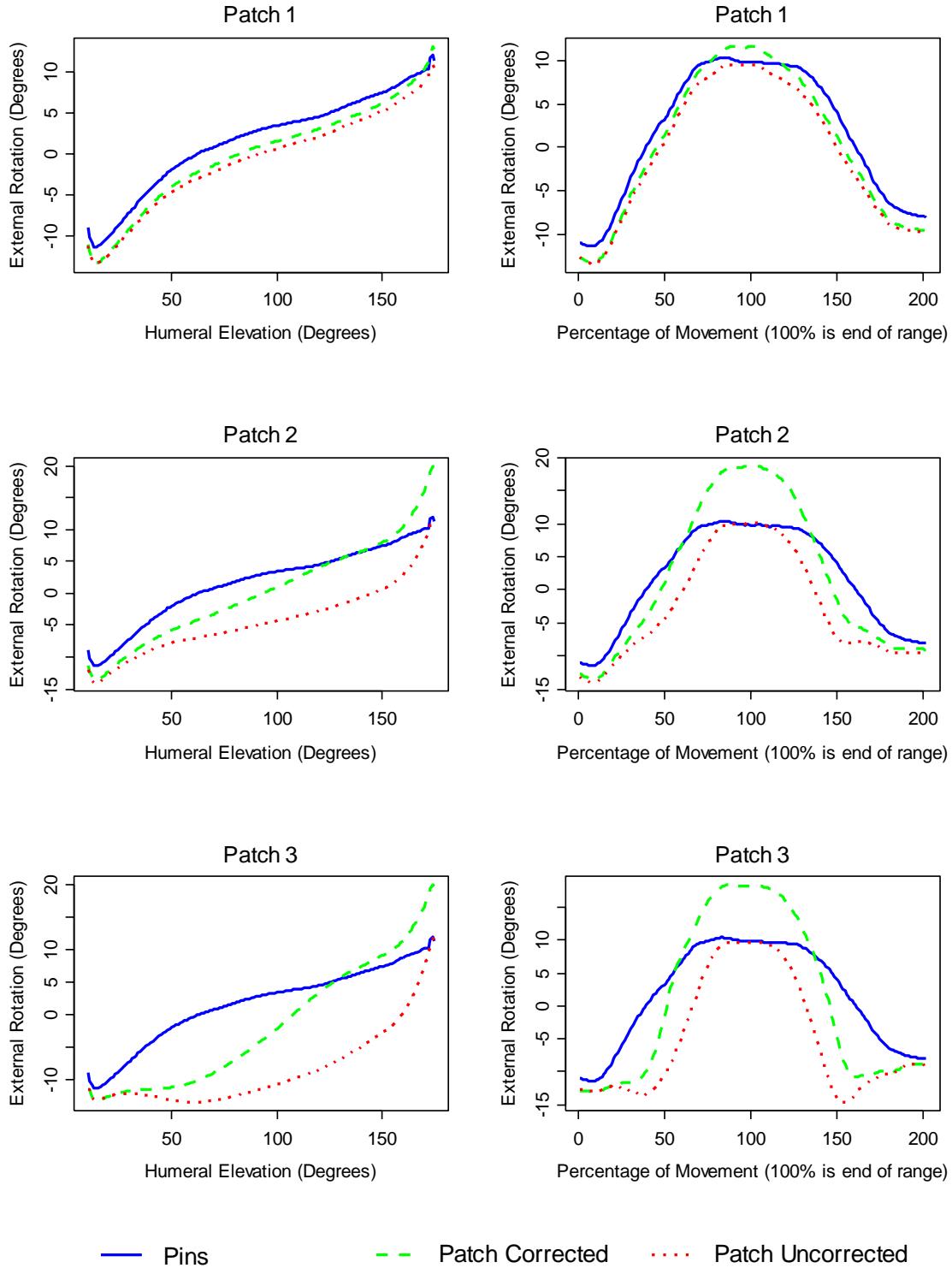
# Abduction: Pins vs. Patches Subject1

## External Rotation



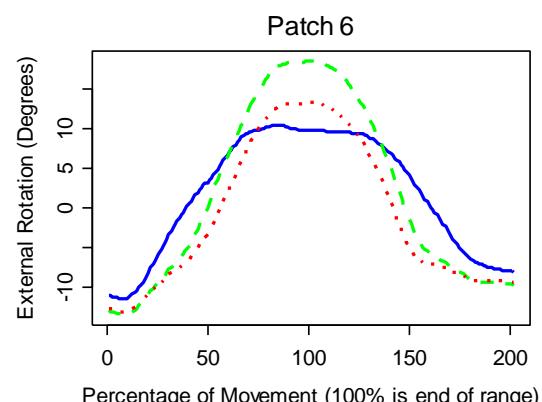
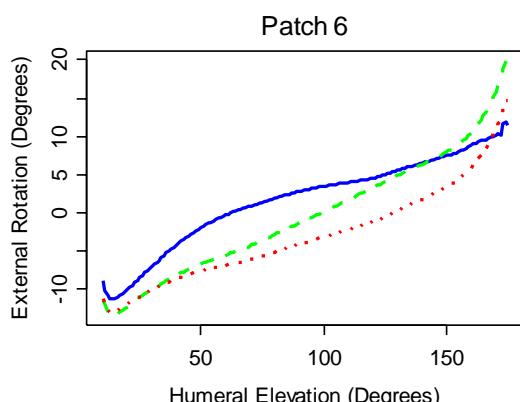
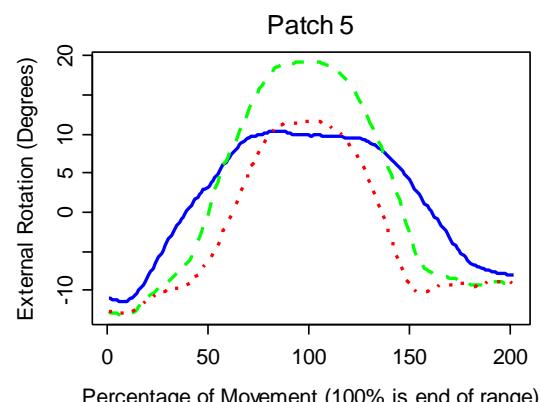
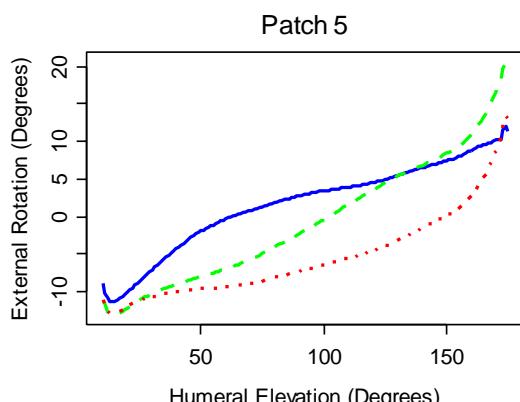
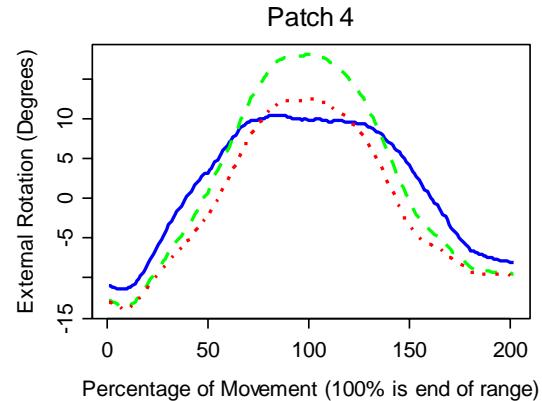
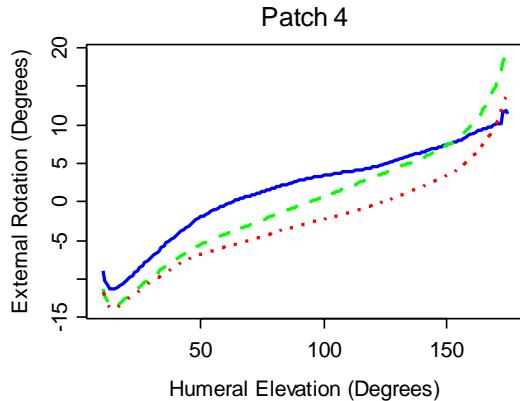
## Abduction: Pins vs. Patches Subject2

### External Rotation



## Abduction: Pins vs. Patches Subject2

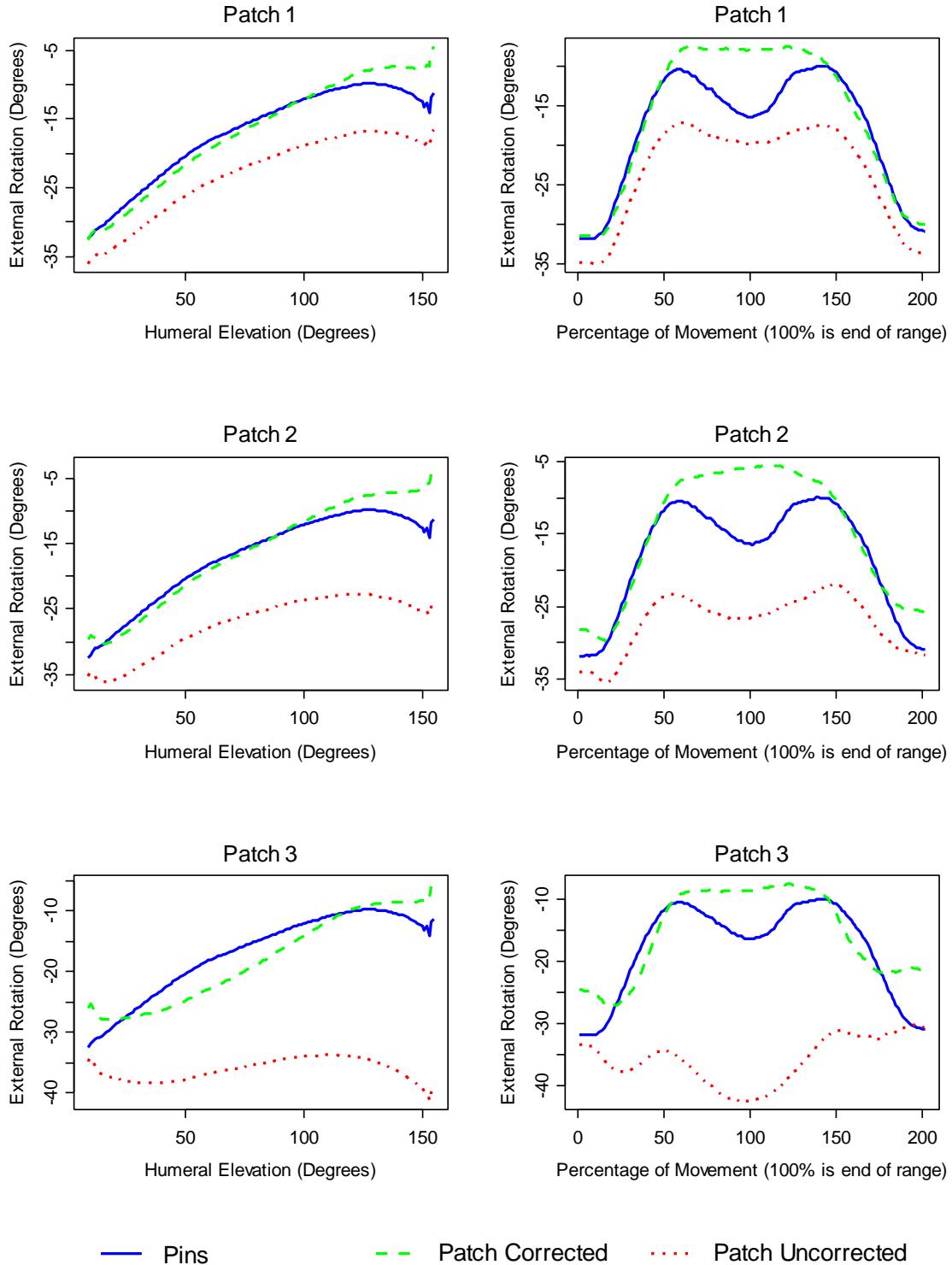
### External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

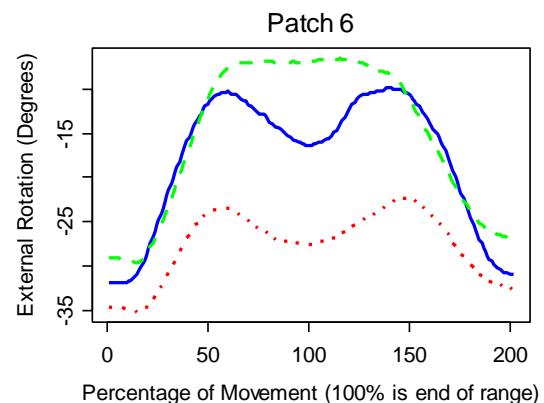
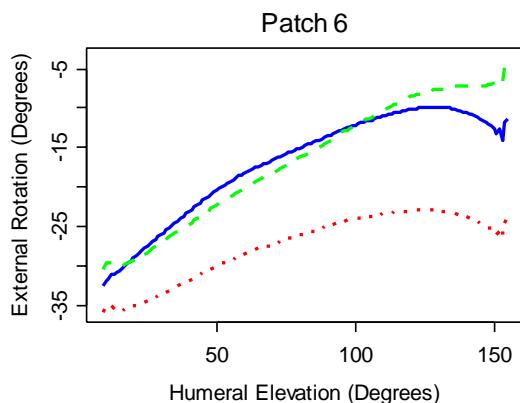
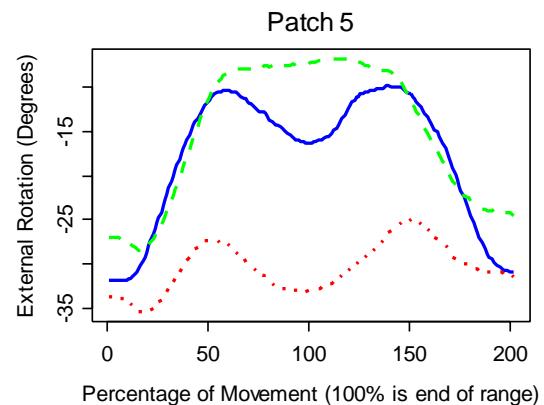
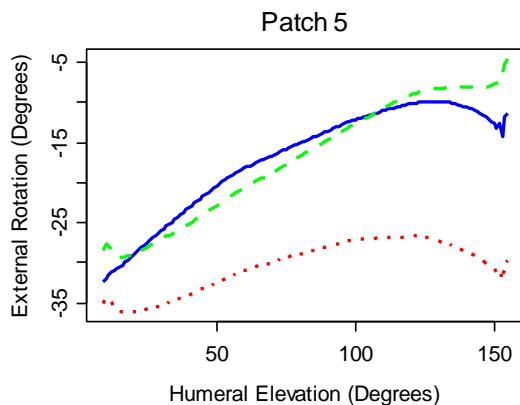
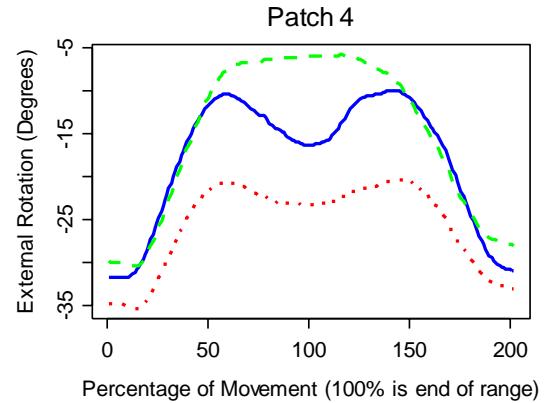
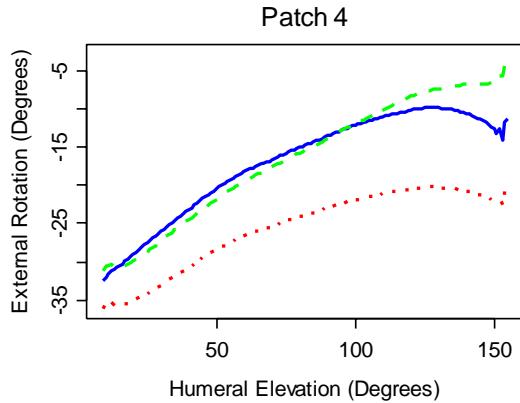
# Abduction: Pins vs. Patches Subject3

## External Rotation



# Abduction: Pins vs. Patches Subject3

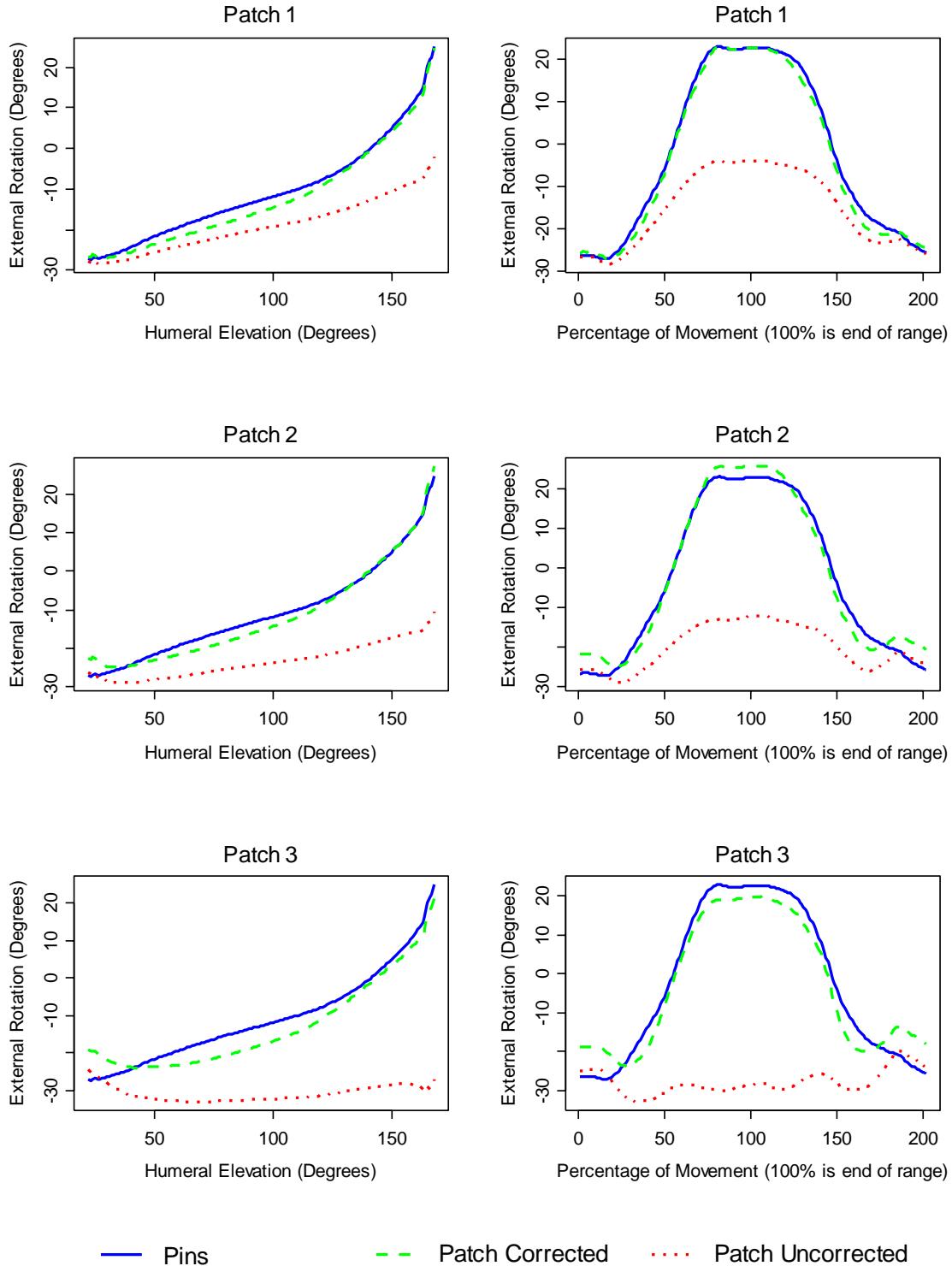
## External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

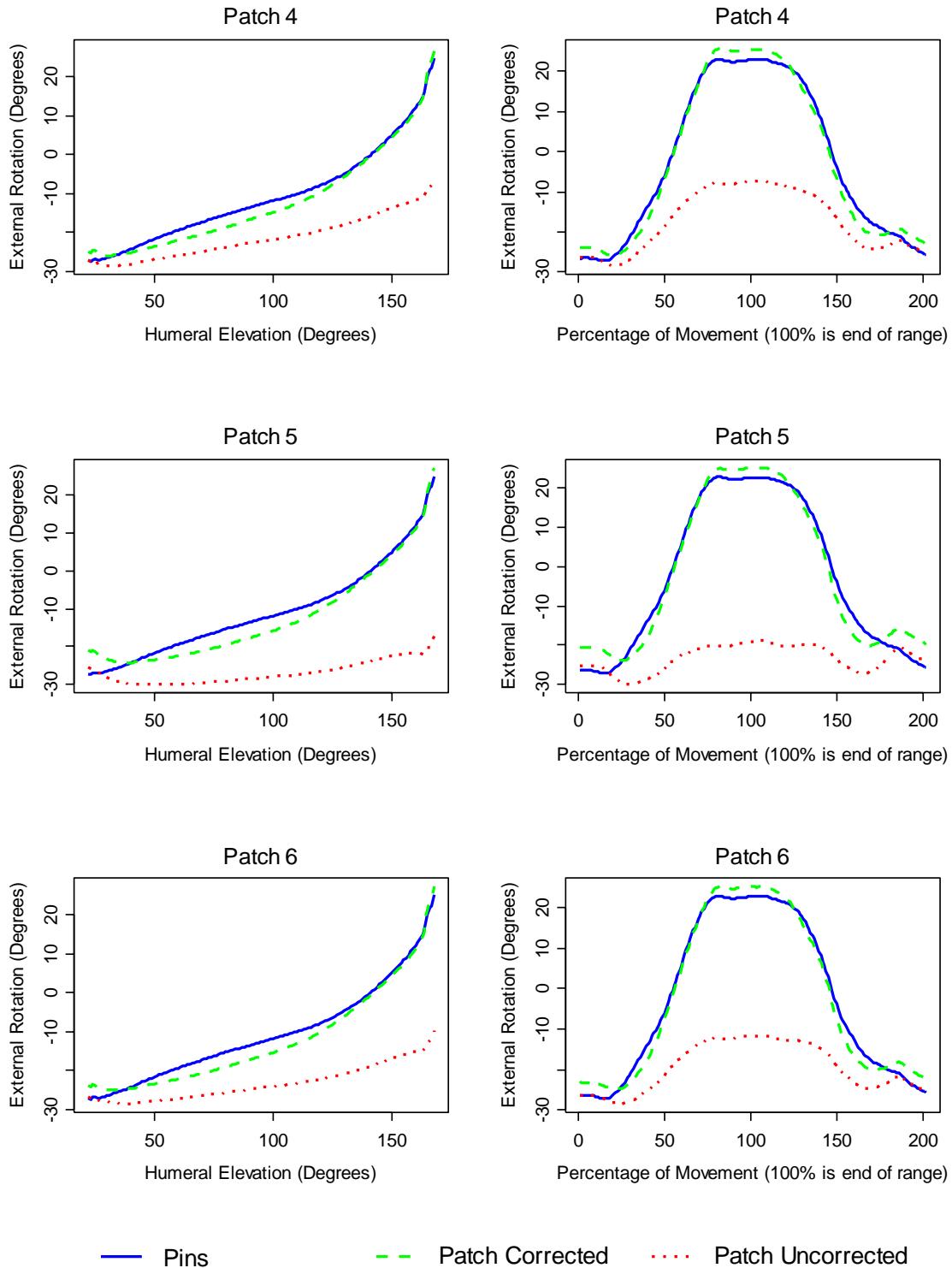
## Abduction: Pins vs. Patches Subject4

### External Rotation



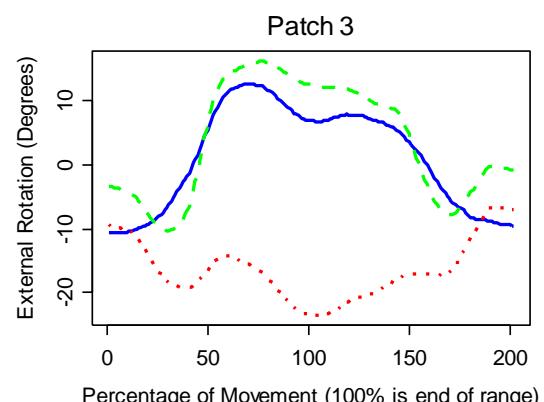
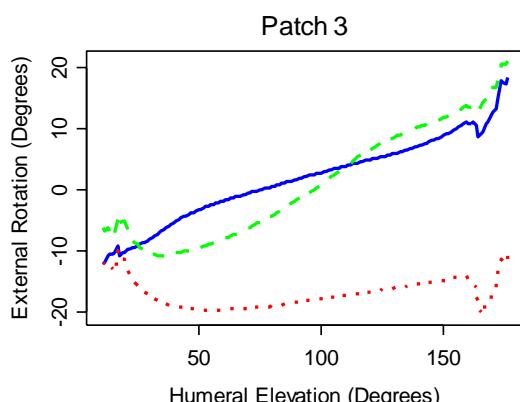
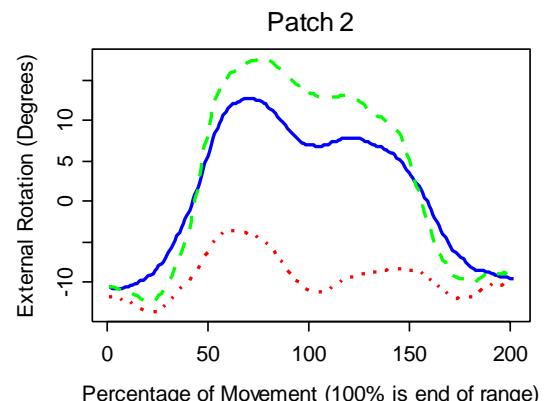
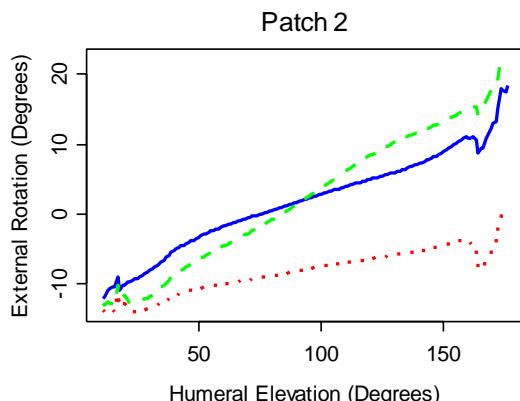
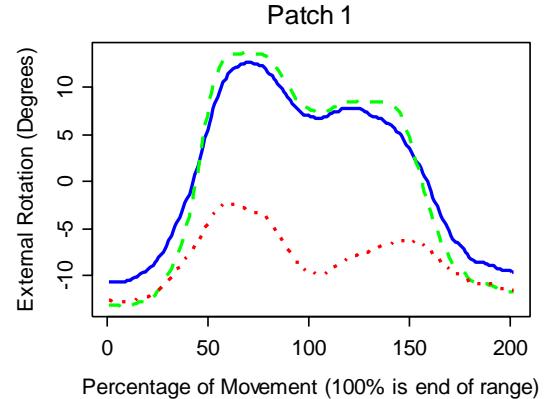
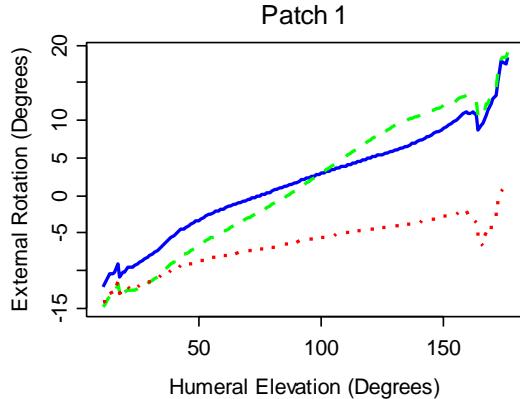
## Abduction: Pins vs. Patches Subject4

### External Rotation



# Abduction: Pins vs. Patches Subject5

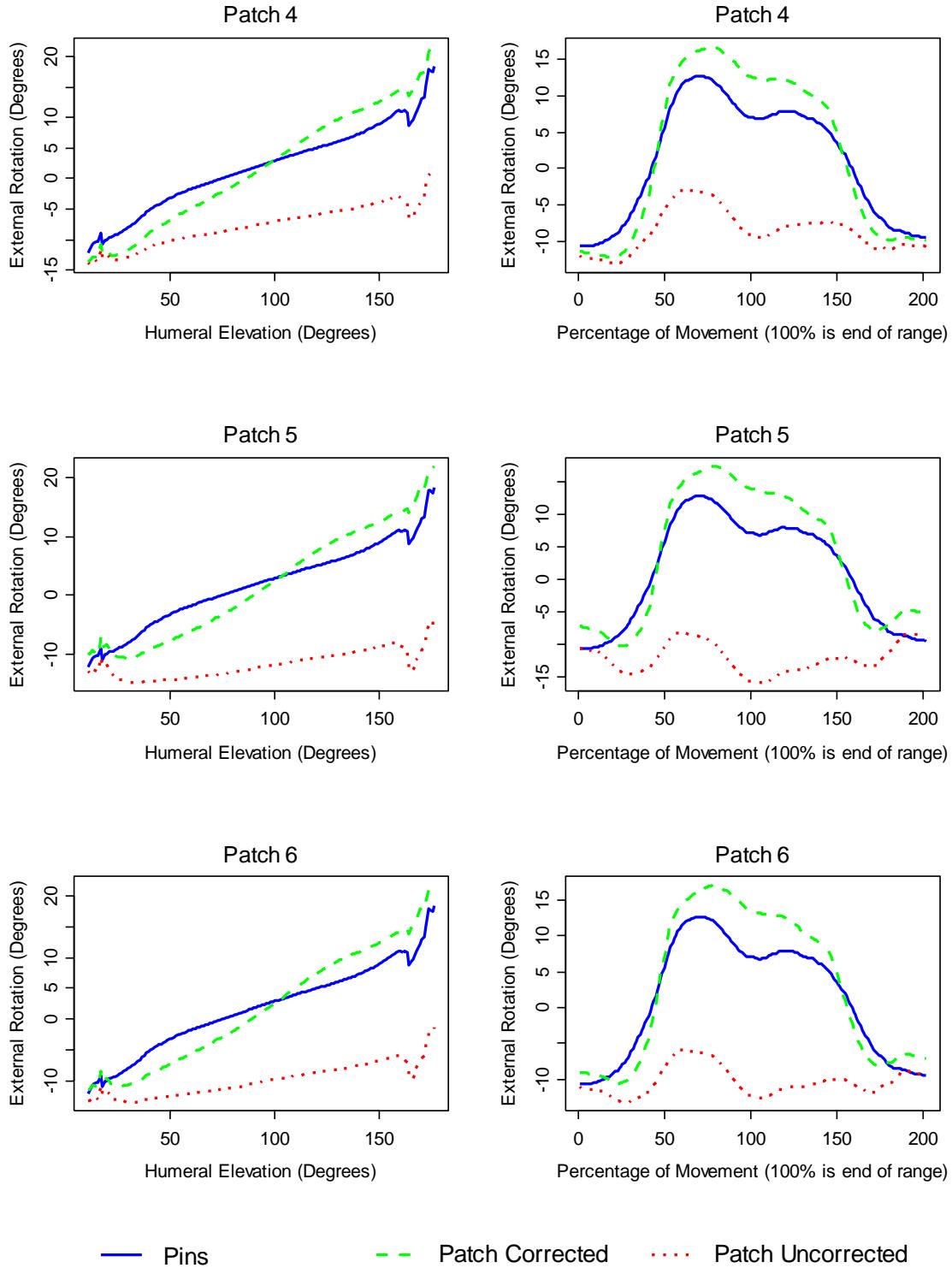
## External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

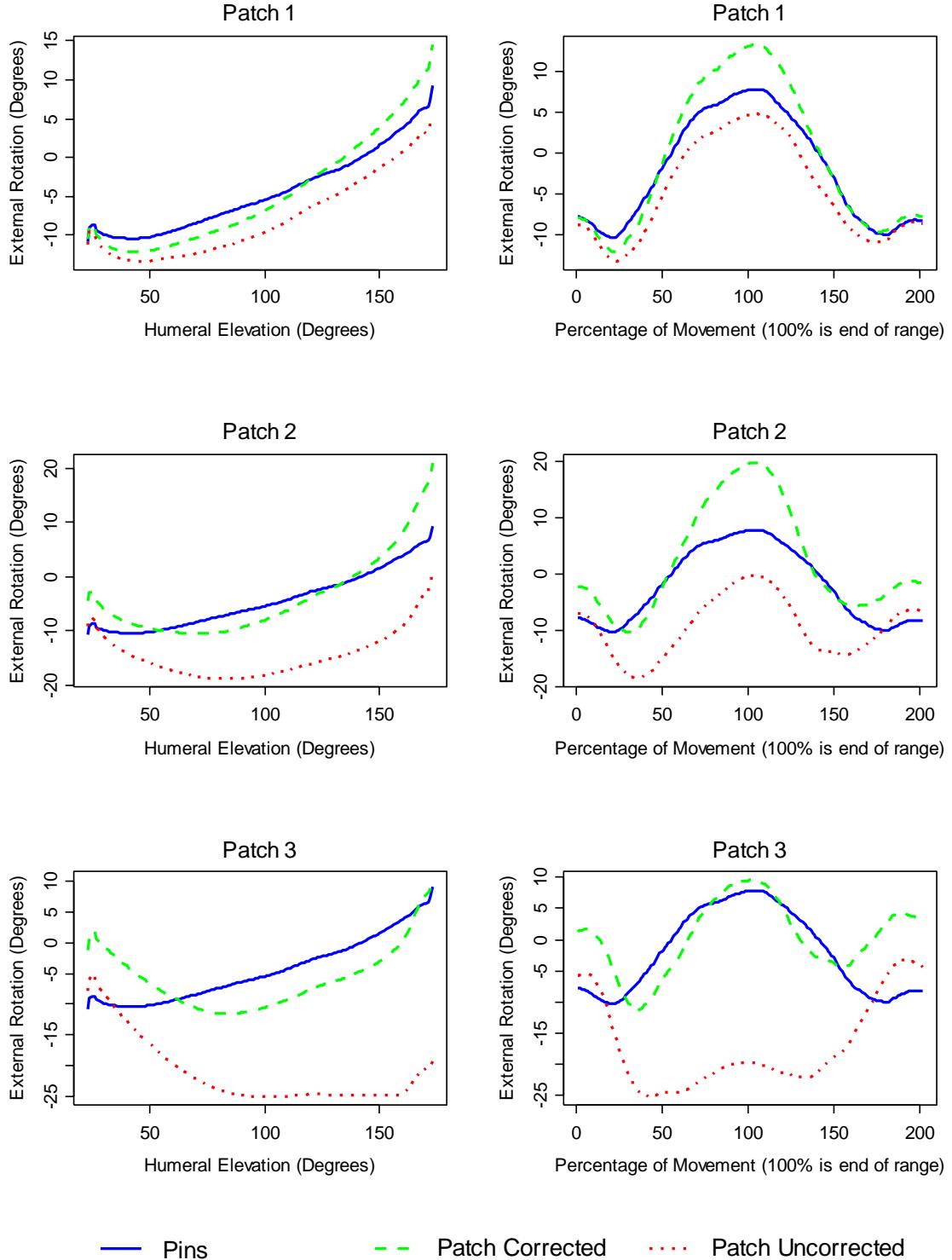
# Abduction: Pins vs. Patches Subject5

## External Rotation



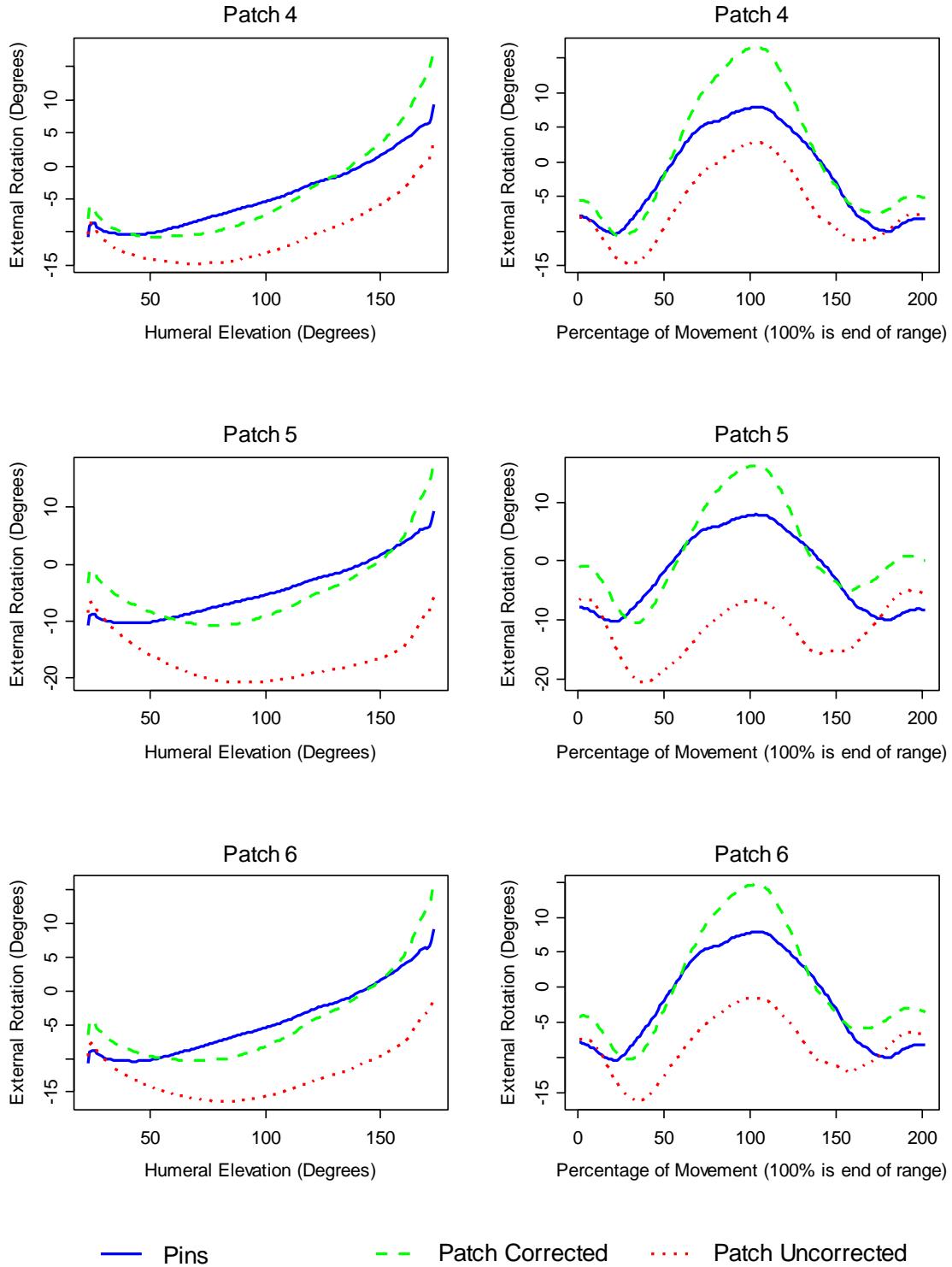
# Abduction: Pins vs. Patches Subject6

## External Rotation



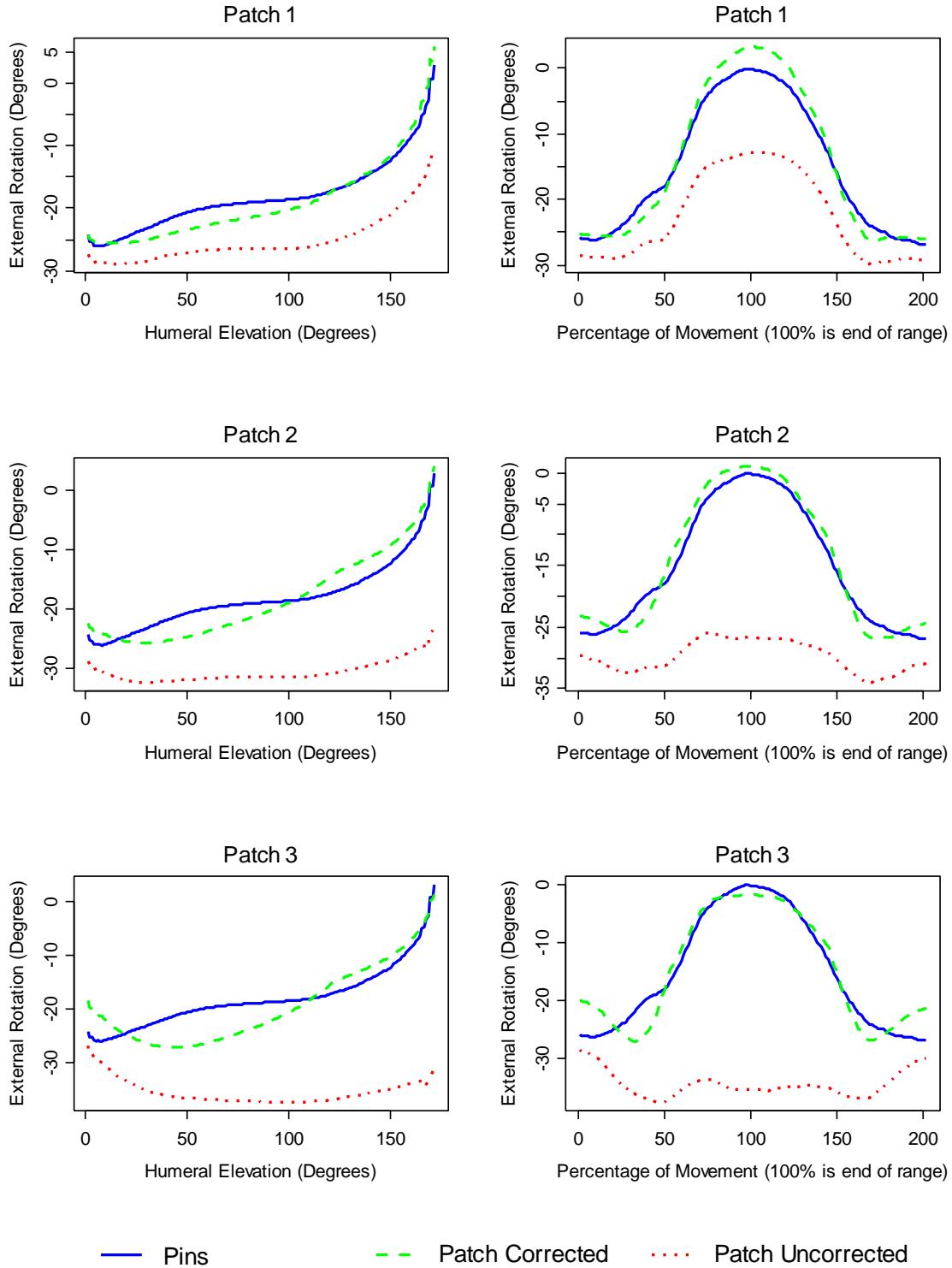
# Abduction: Pins vs. Patches Subject6

## External Rotation



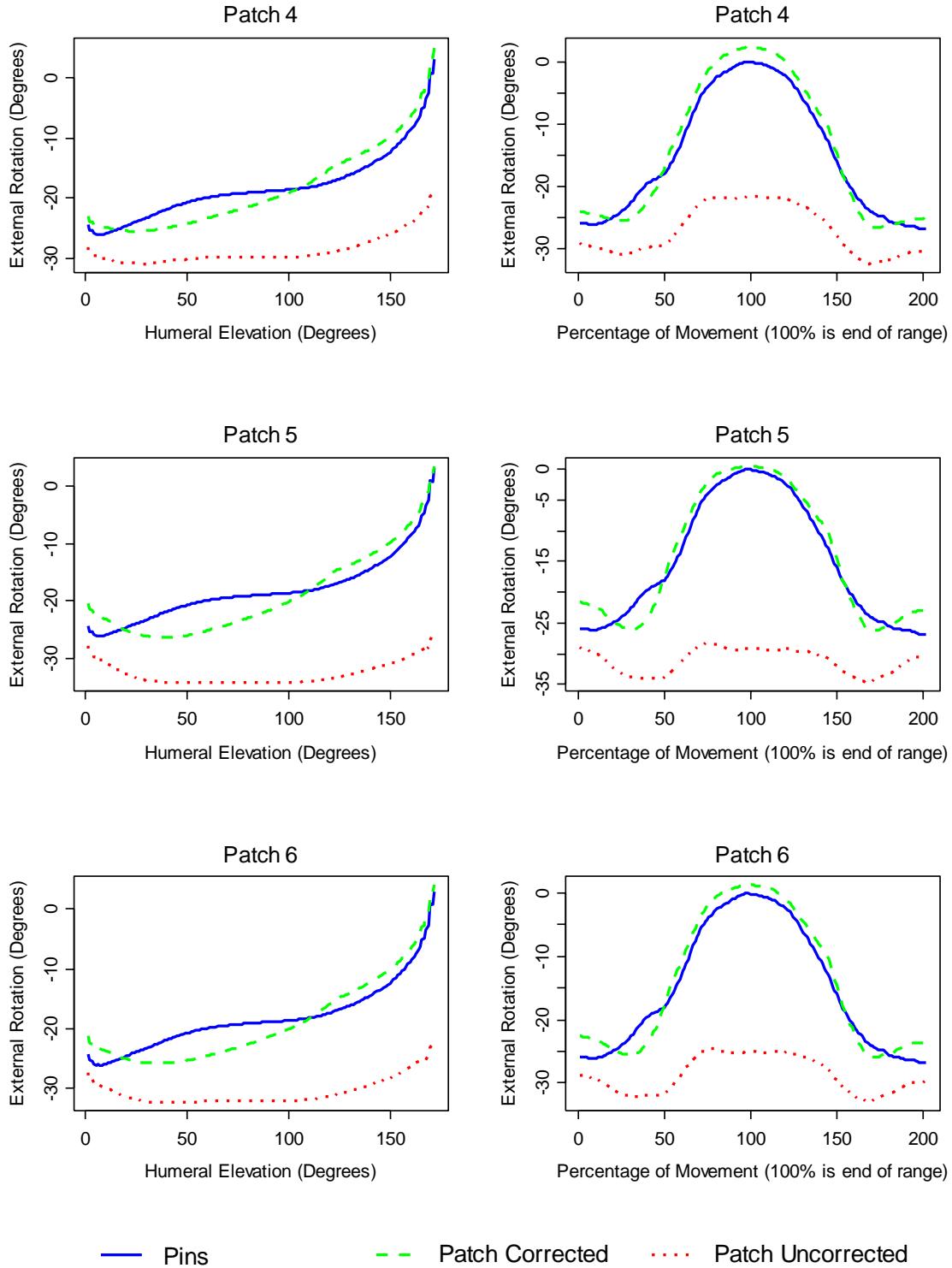
# Abduction: Pins vs. Patches Subject7

## External Rotation



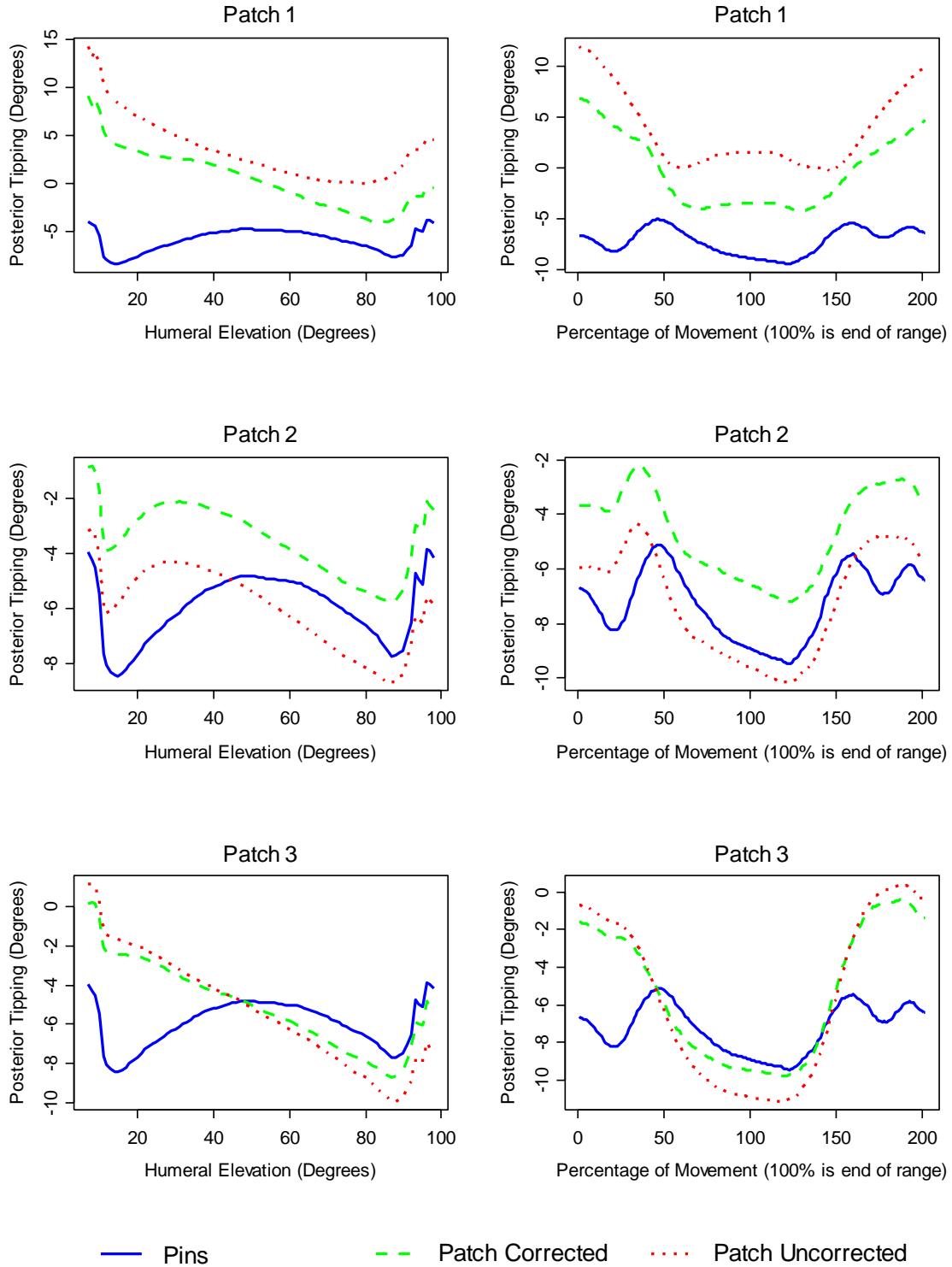
# Abduction: Pins vs. Patches Subject7

## External Rotation



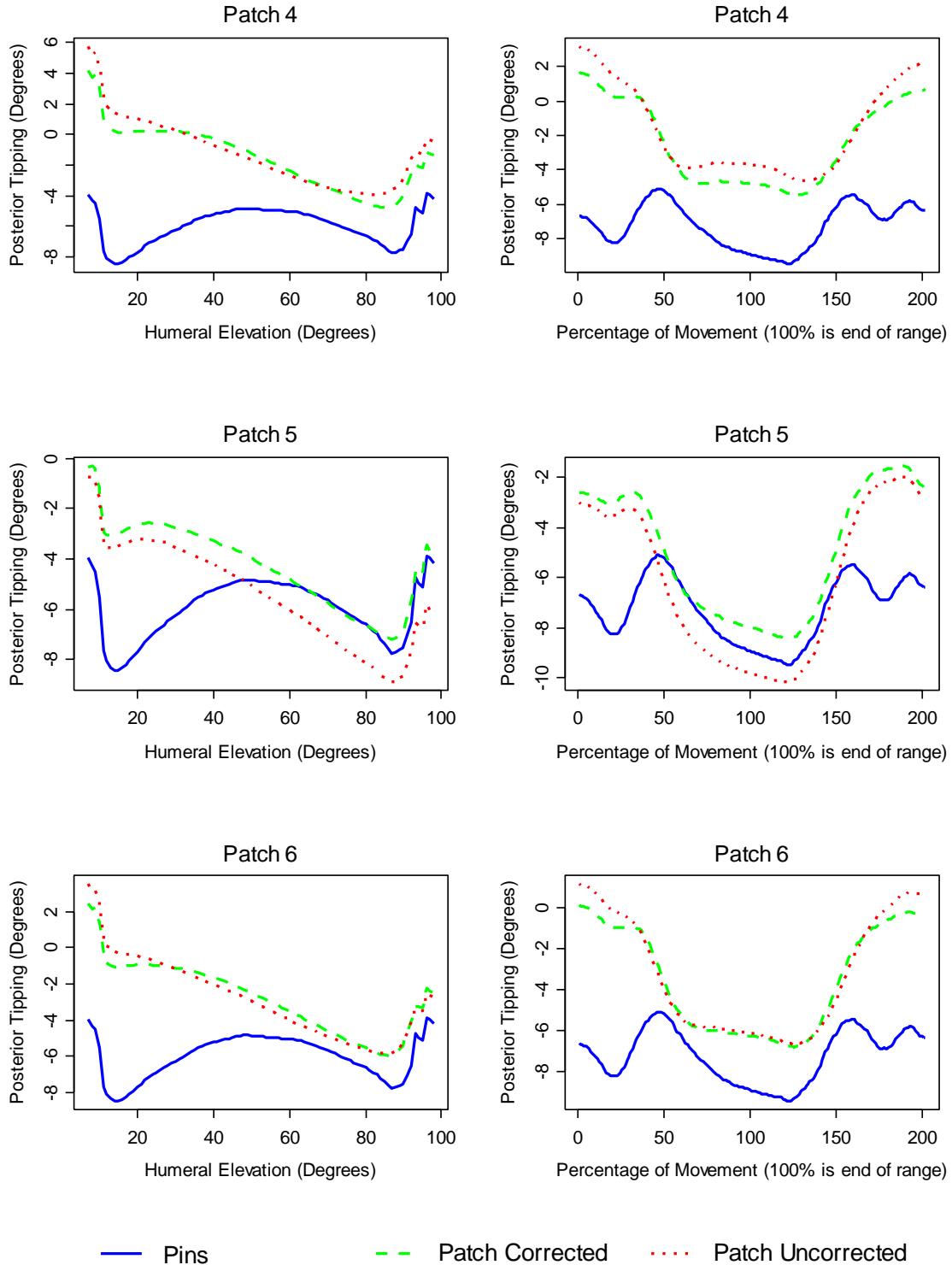
# Reaching: Pins vs. Patches Subject1

## Posterior Tipping

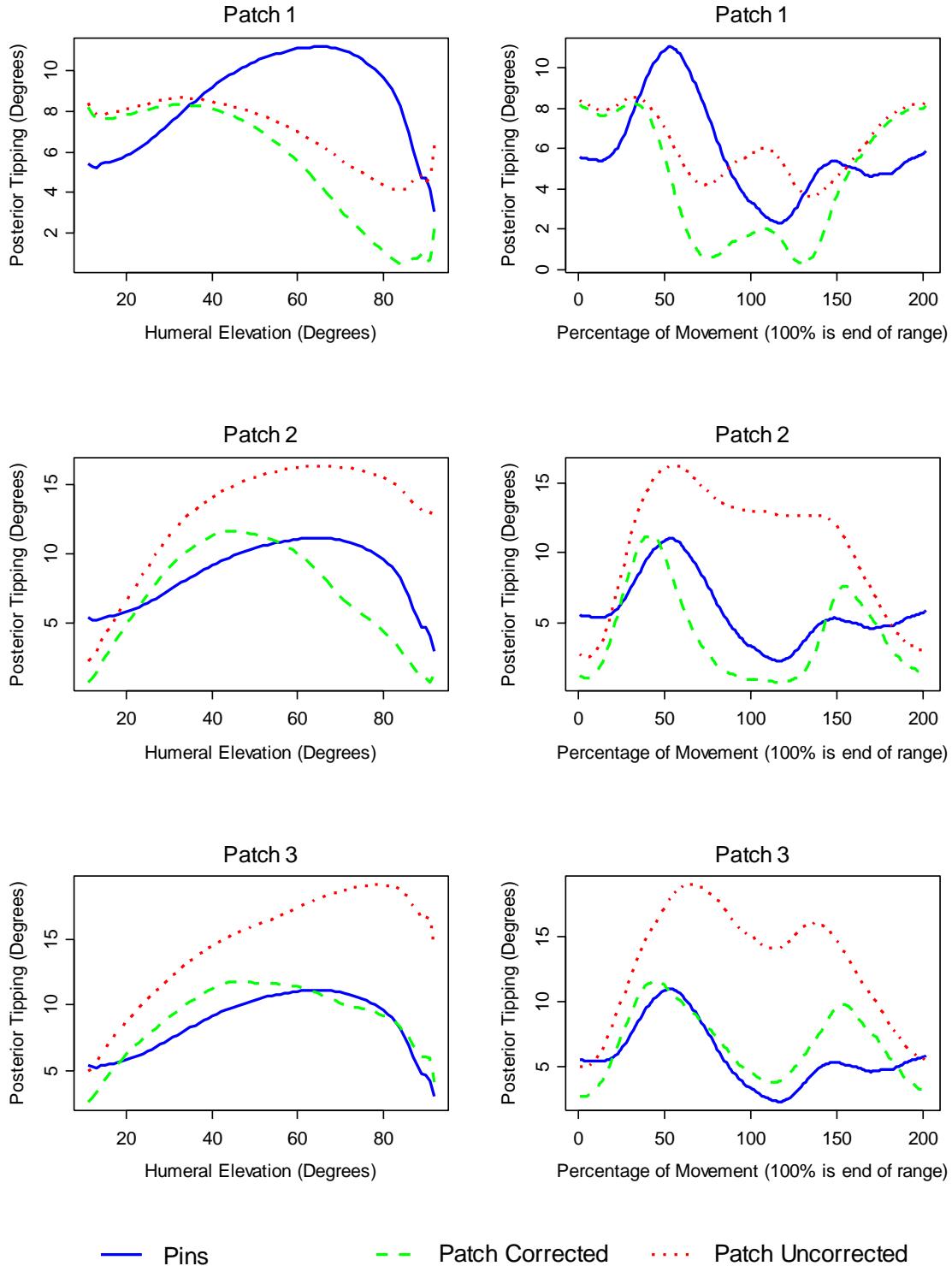


# Reaching: Pins vs. Patches Subject1

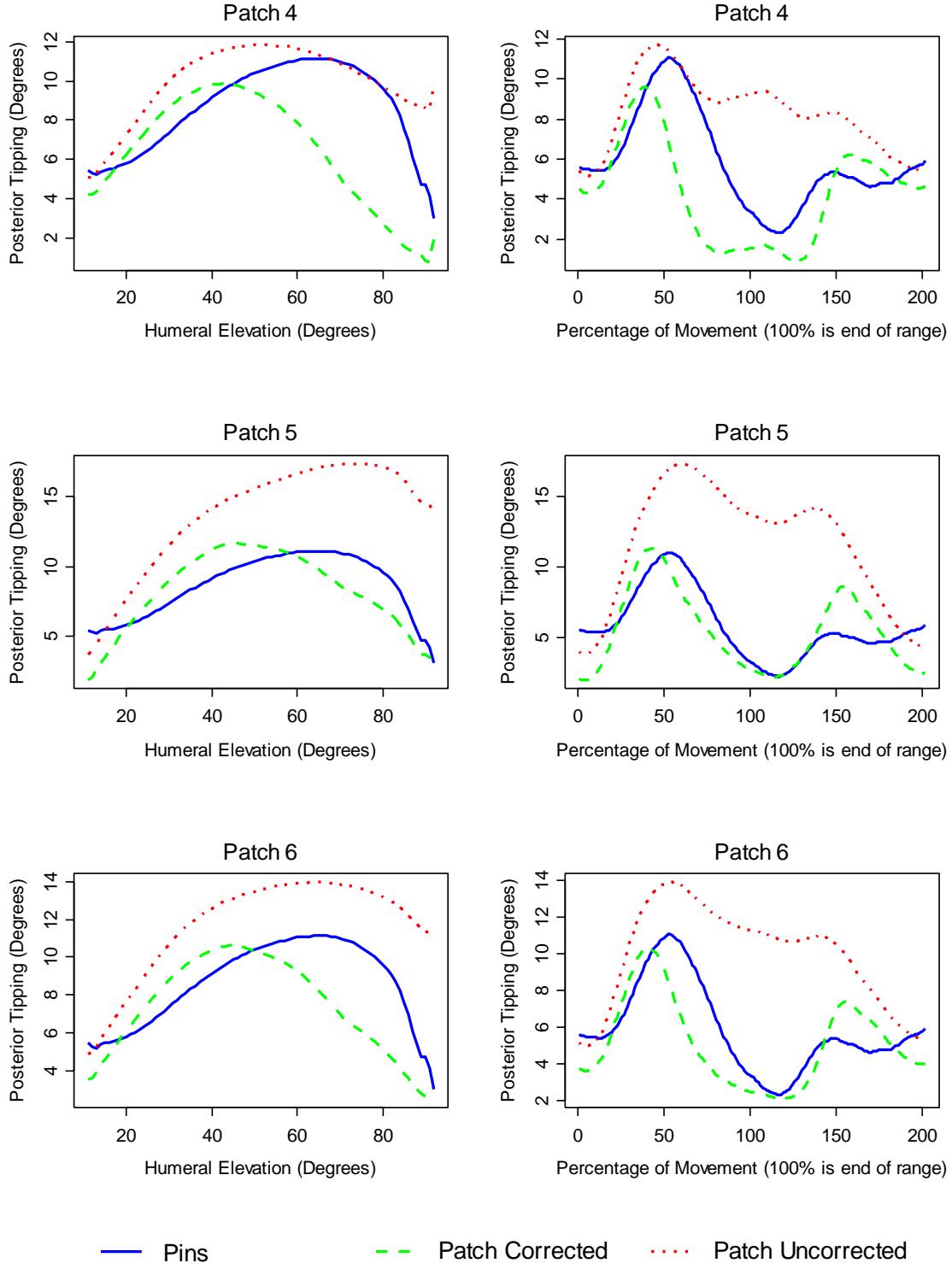
## Posterior Tipping



## Reaching: Pins vs. Patches Subject2 Posterior Tipping

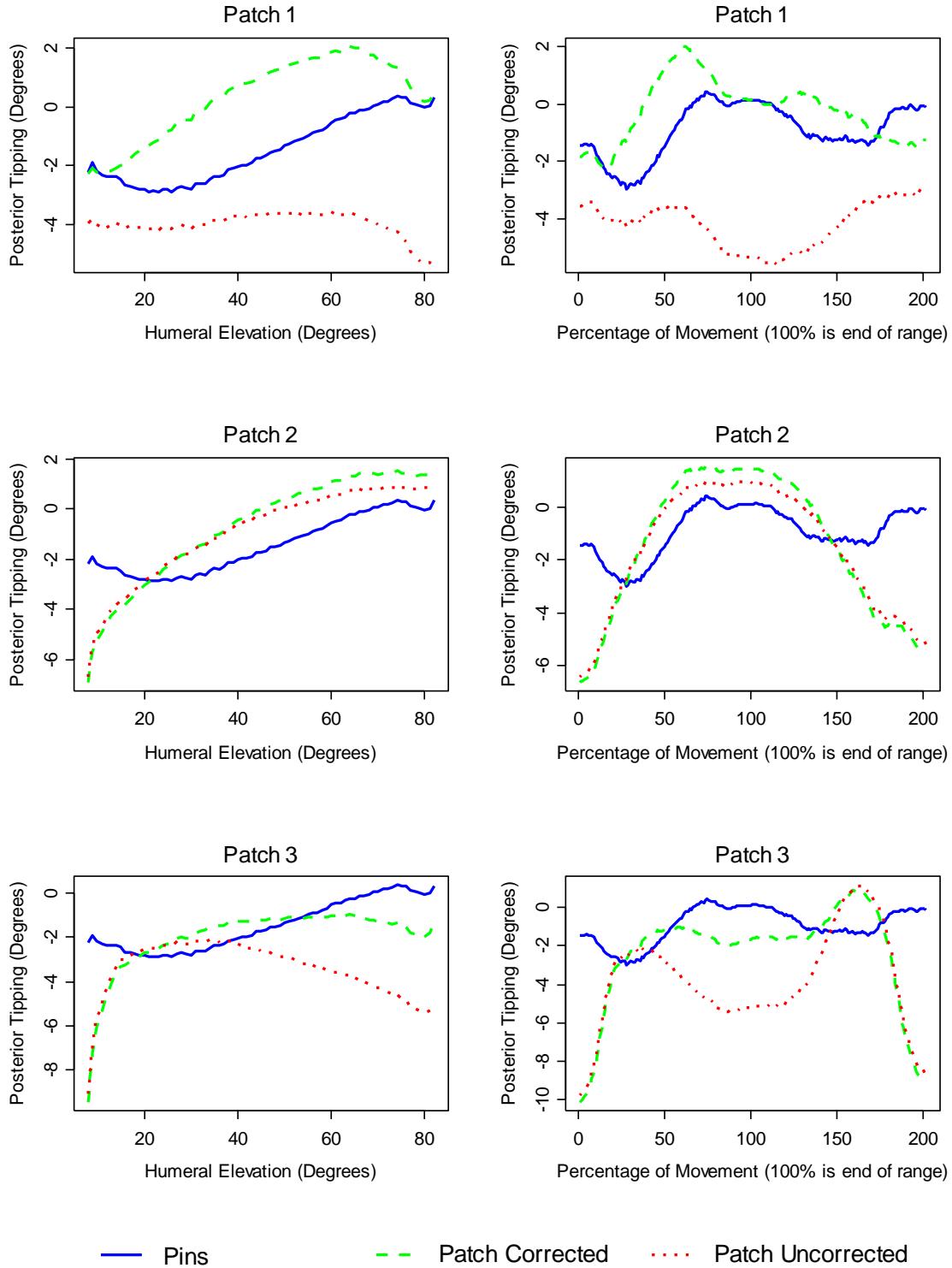


## Reaching: Pins vs. Patches Subject2 Posterior Tipping



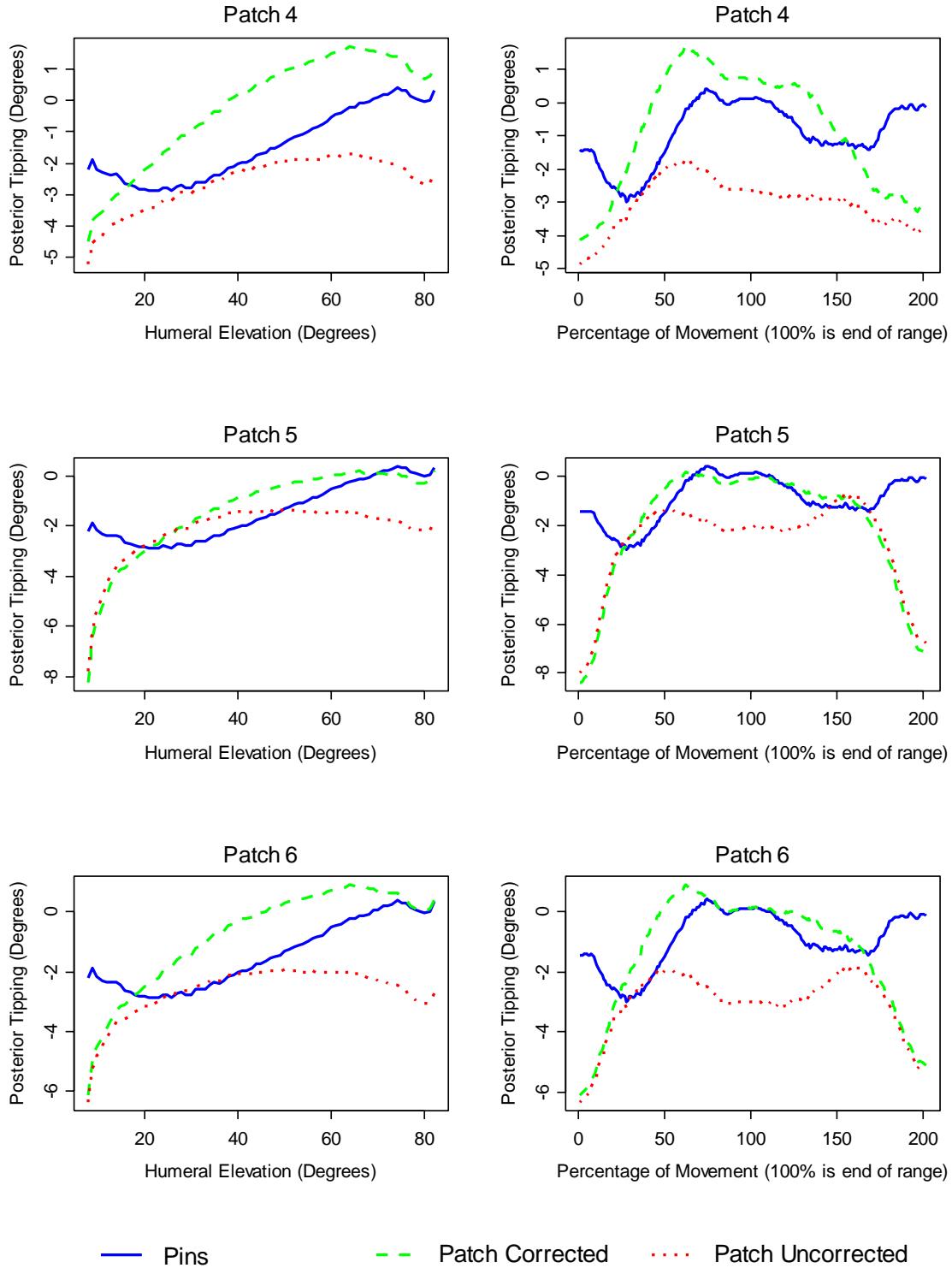
# Reaching: Pins vs. Patches Subject3

## Posterior Tipping



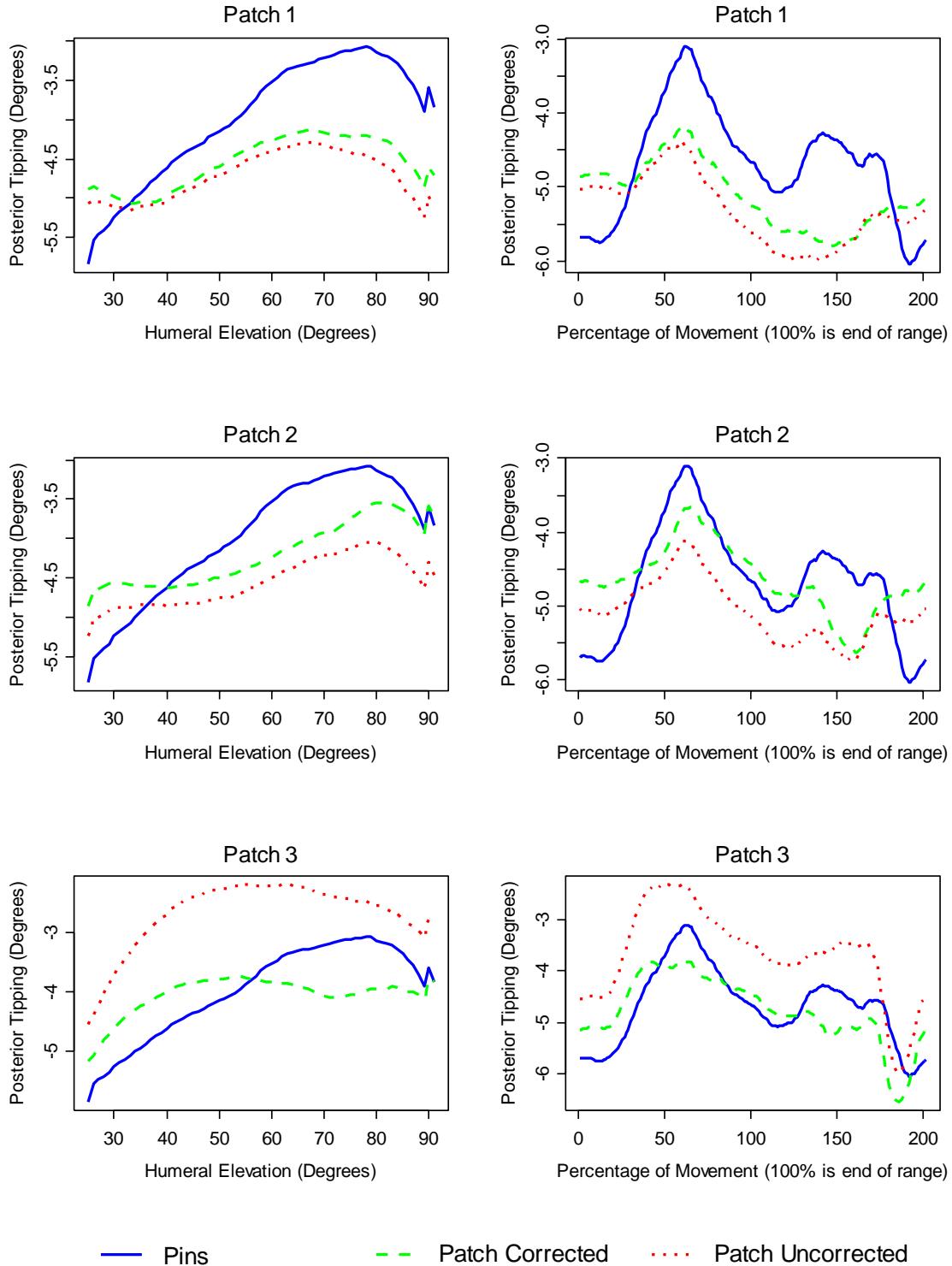
# Reaching: Pins vs. Patches Subject3

## Posterior Tipping



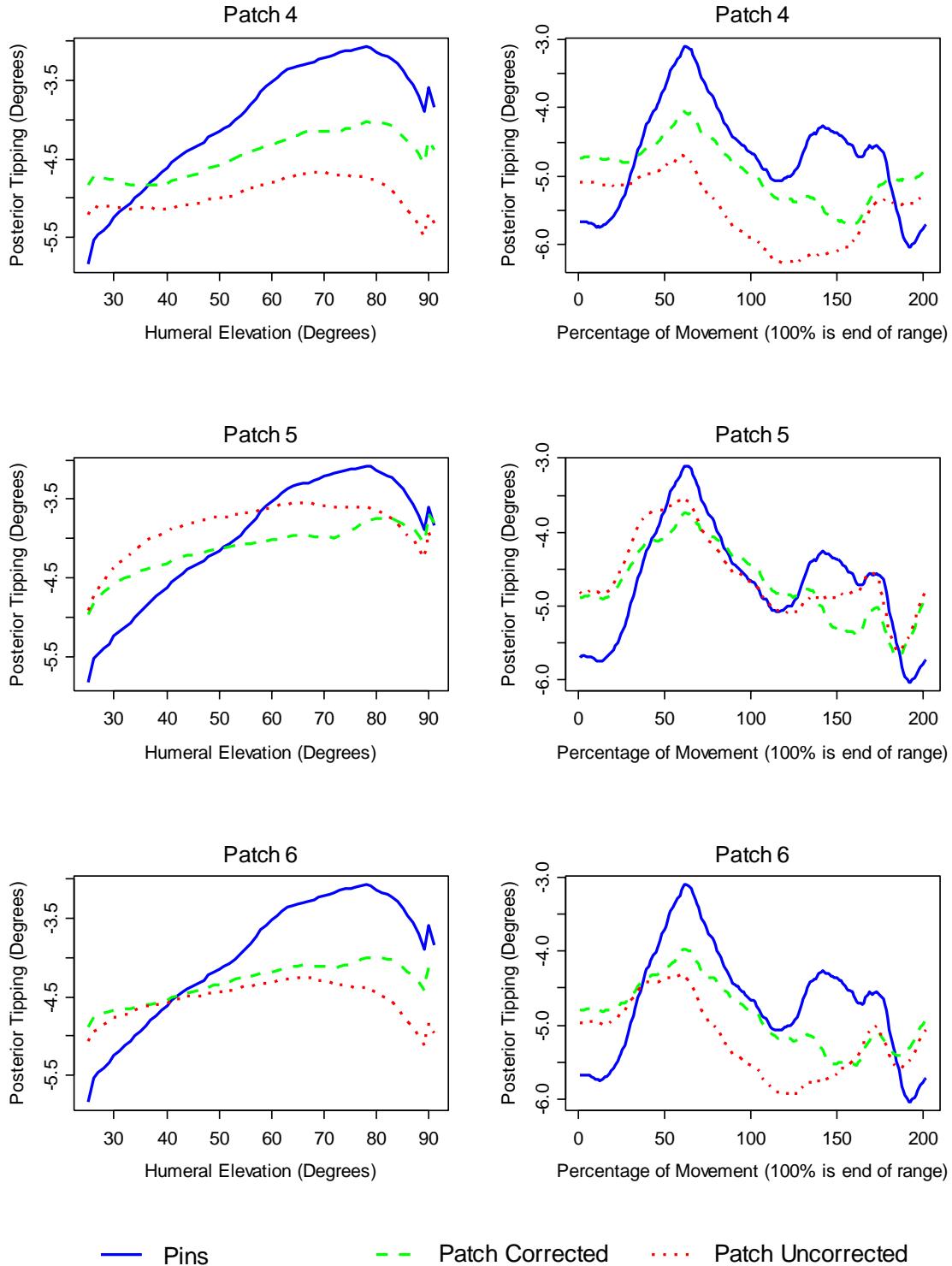
# Reaching: Pins vs. Patches Subject4

## Posterior Tipping



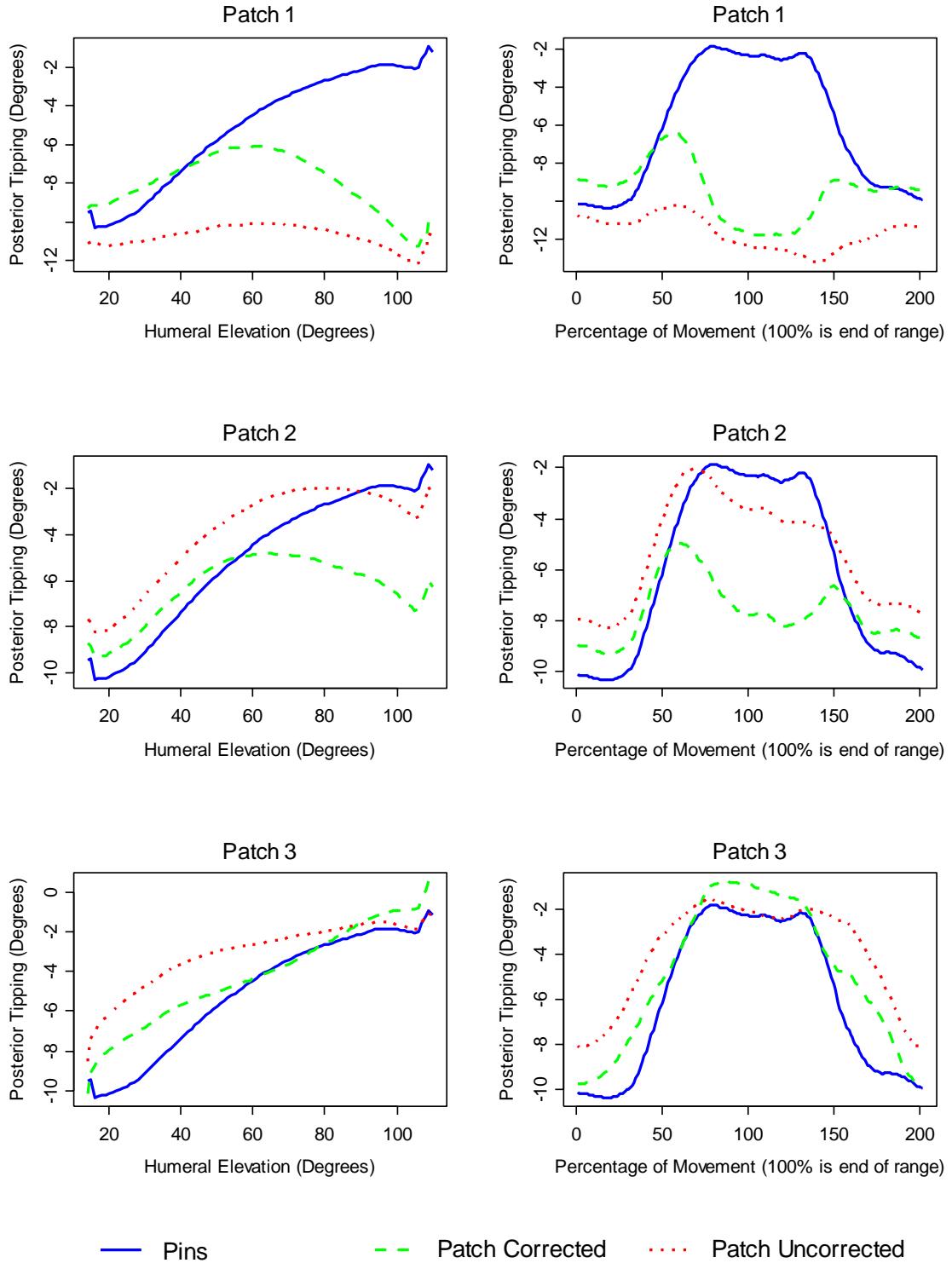
# Reaching: Pins vs. Patches Subject4

## Posterior Tipping



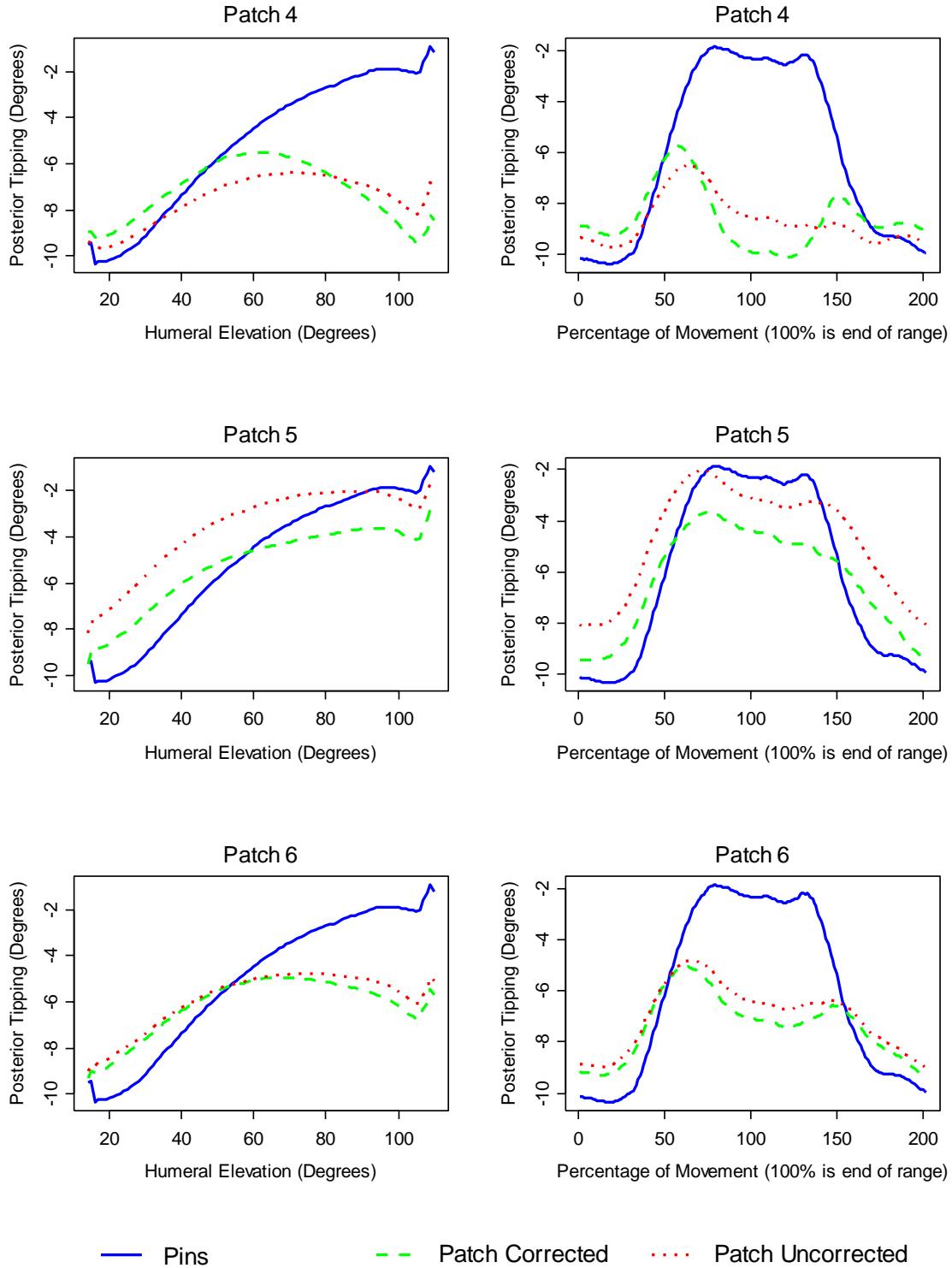
# Reaching: Pins vs. Patches Subject5

## Posterior Tipping



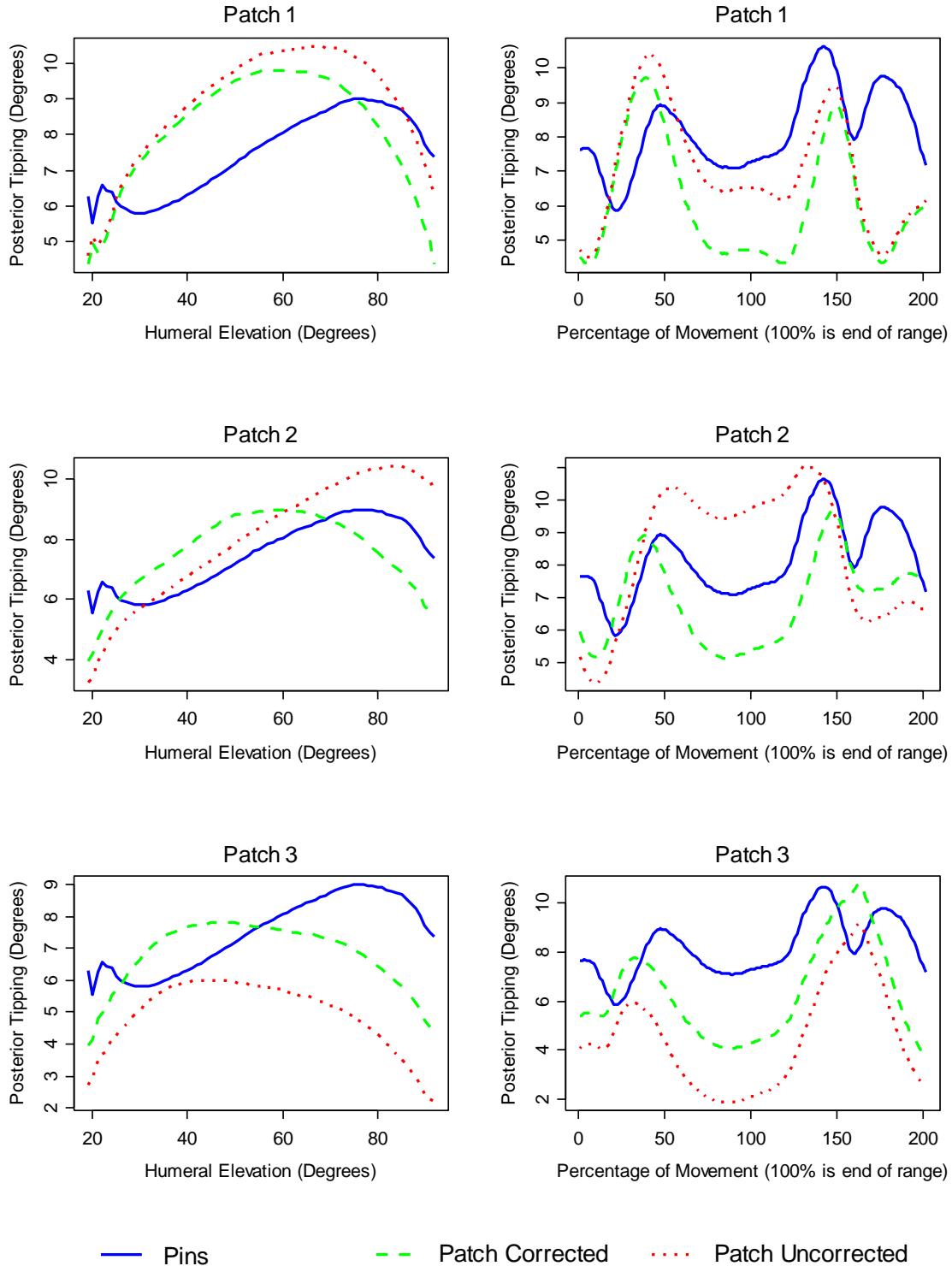
# Reaching: Pins vs. Patches Subject5

## Posterior Tipping



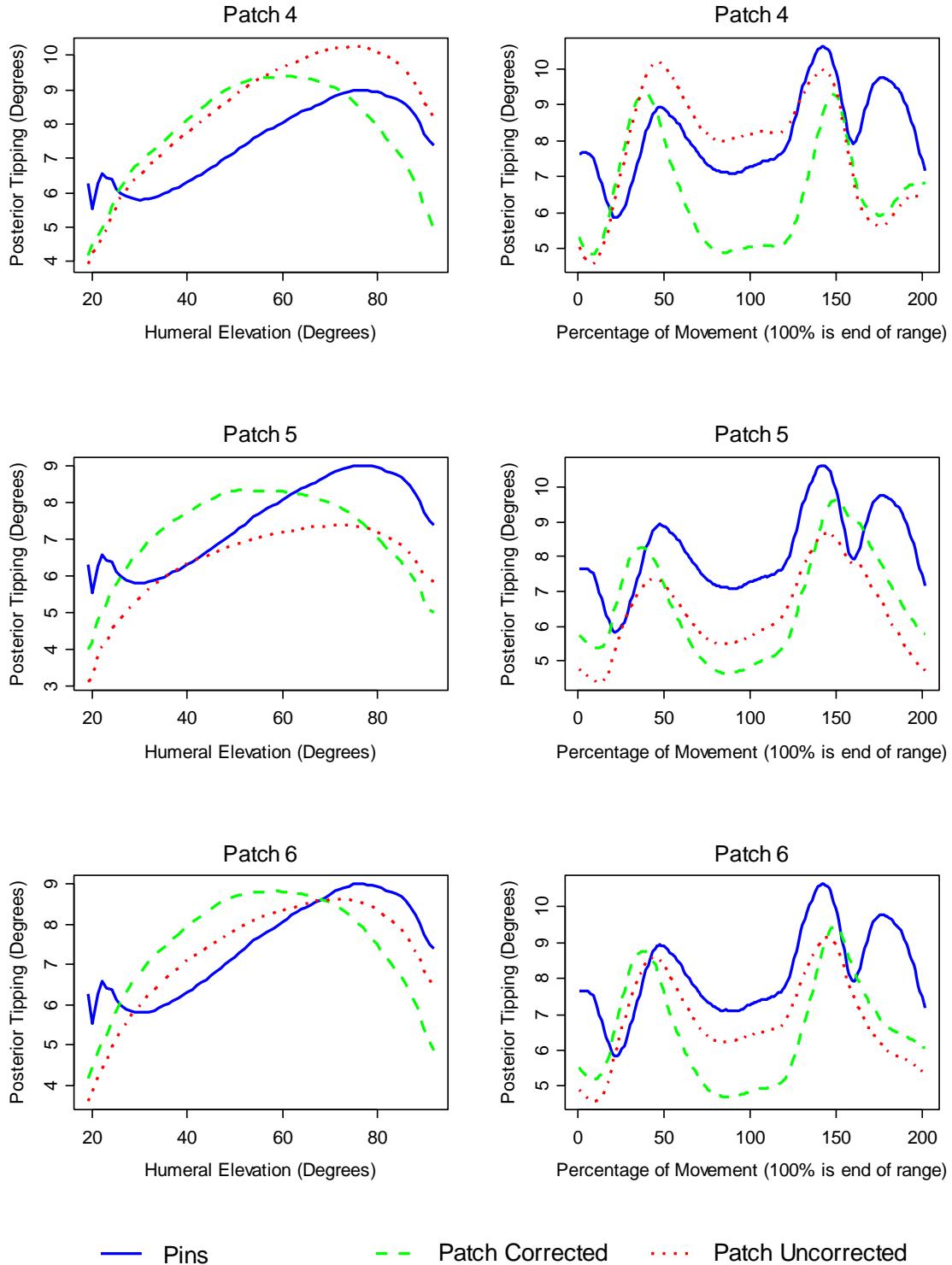
## Reaching: Pins vs. Patches Subject6

### Posterior Tipping



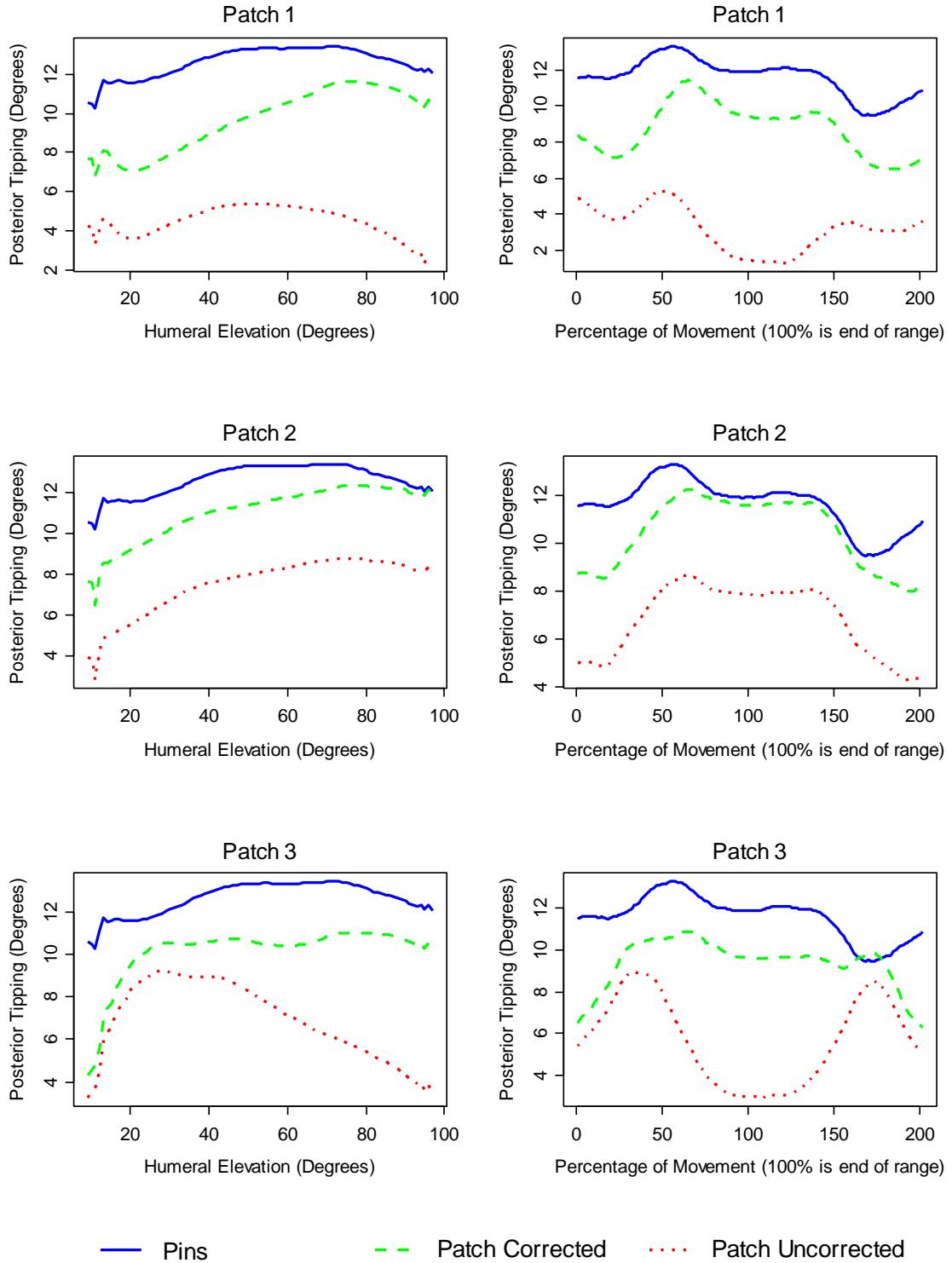
## Reaching: Pins vs. Patches Subject6

### Posterior Tipping



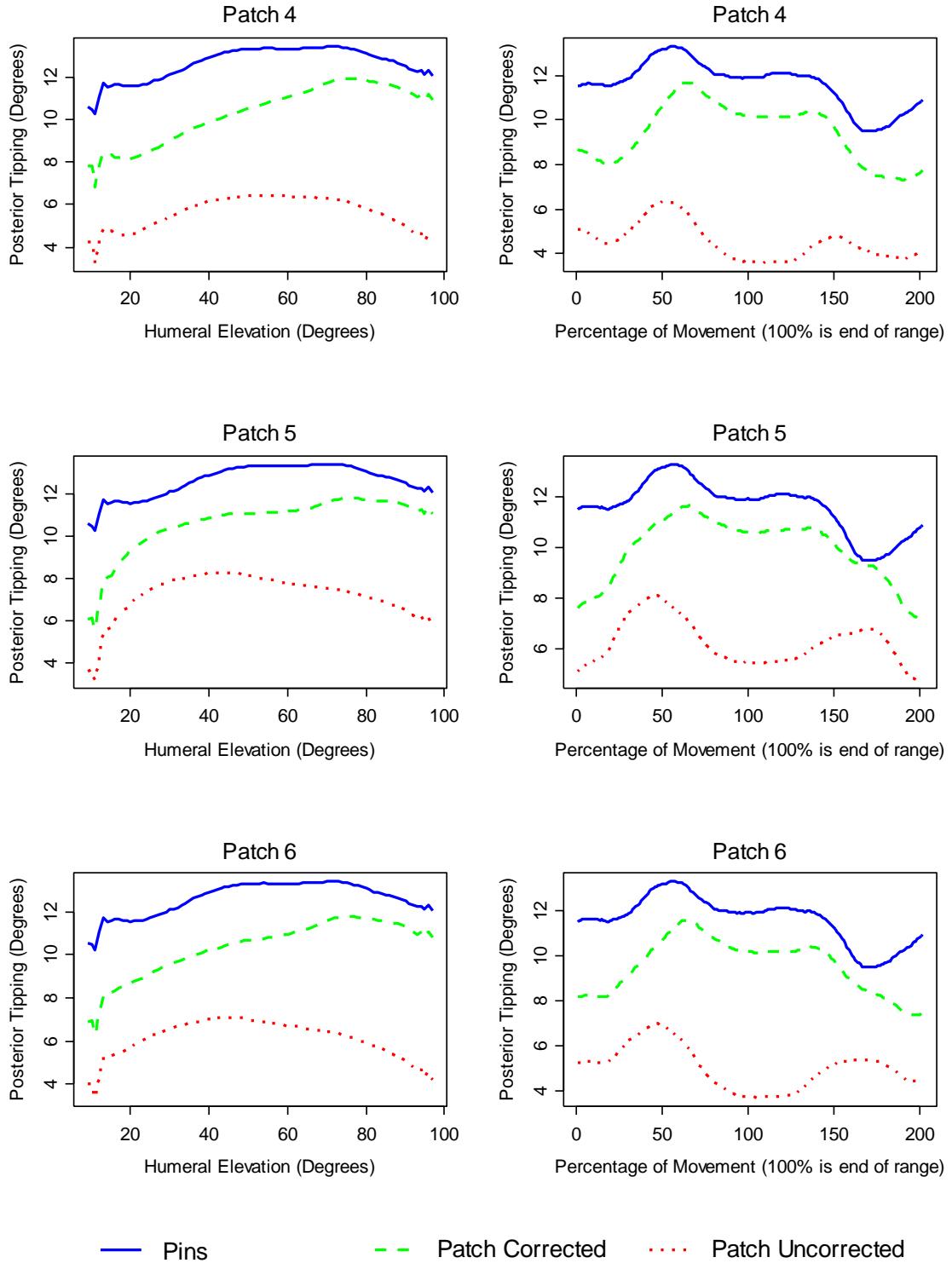
# Reaching: Pins vs. Patches Subject7

## Posterior Tipping



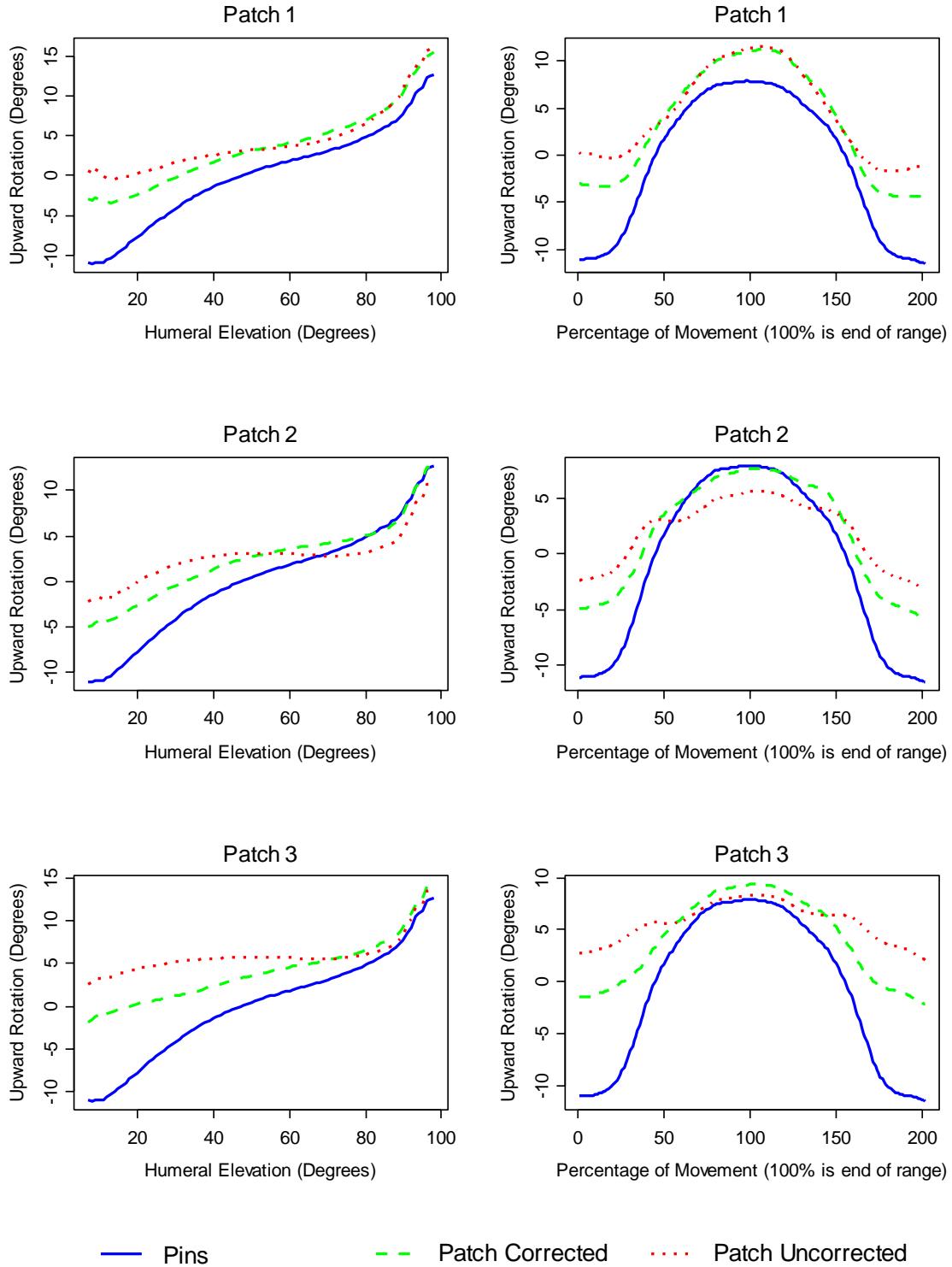
# Reaching: Pins vs. Patches Subject7

## Posterior Tipping



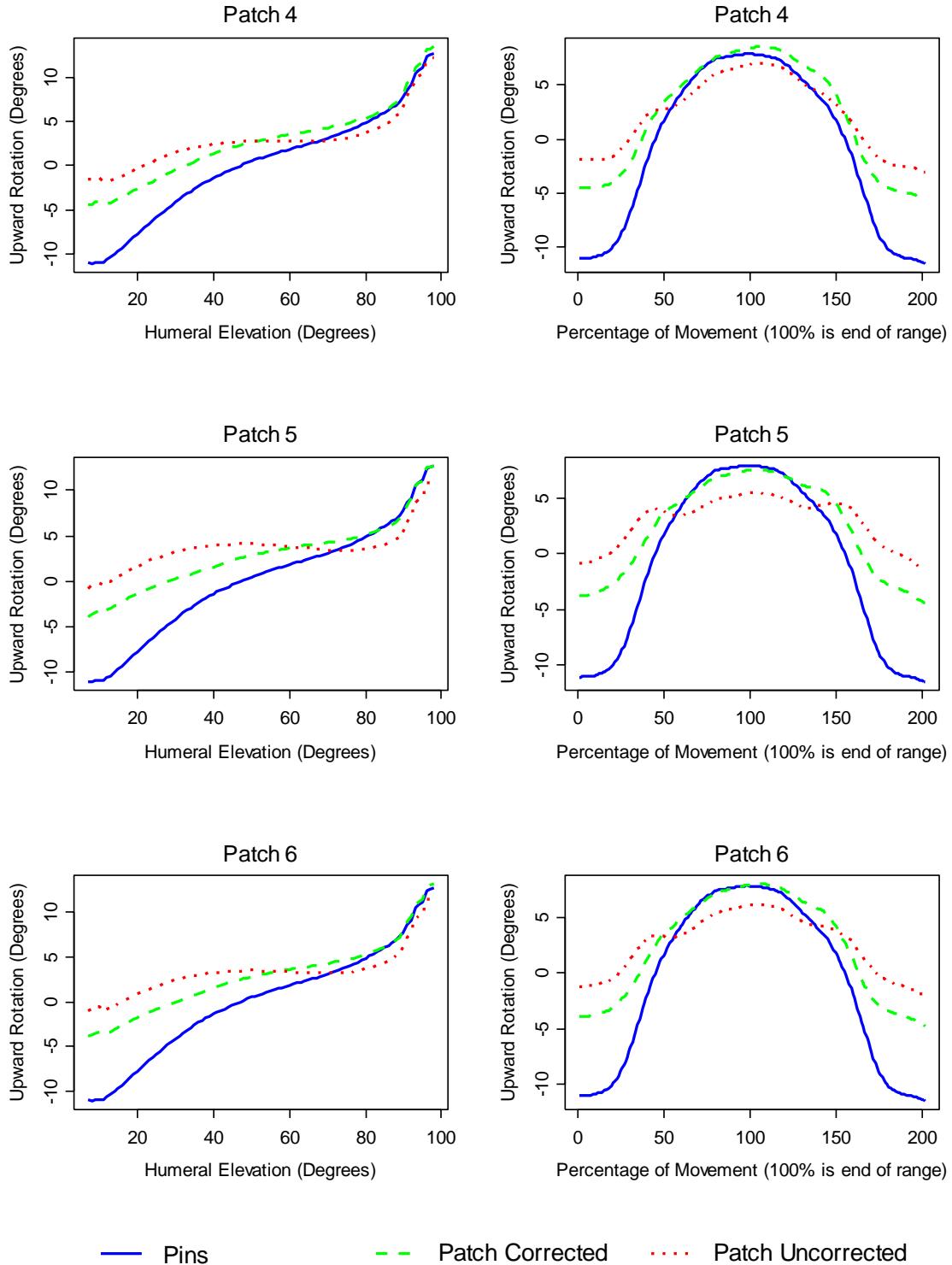
# Reaching: Pins vs. Patches Subject1

## Upward Rotation



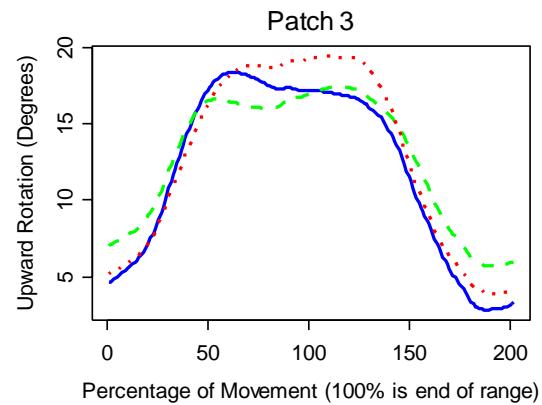
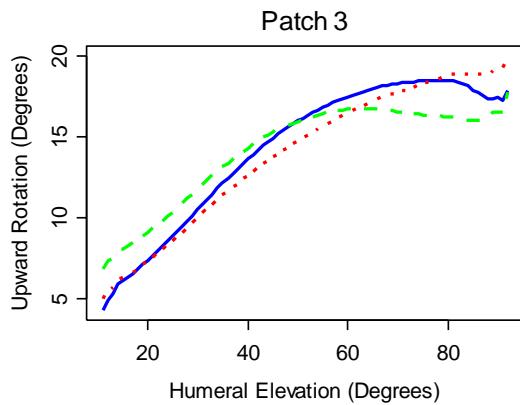
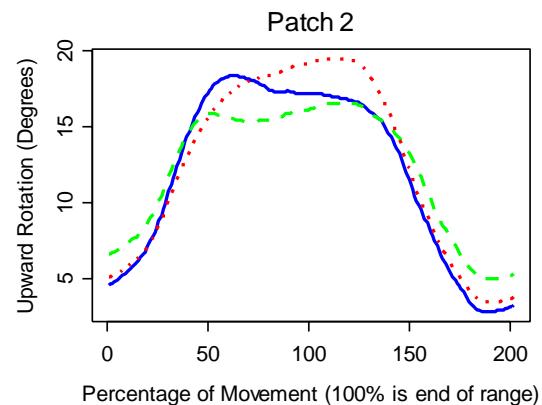
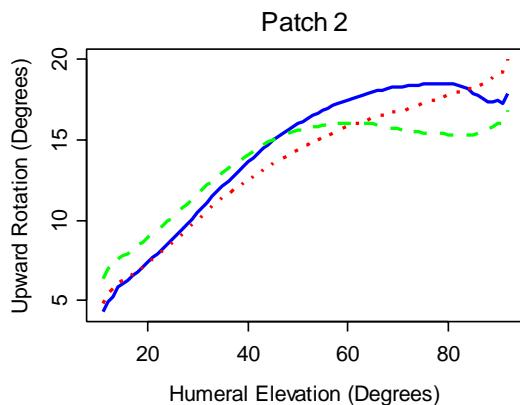
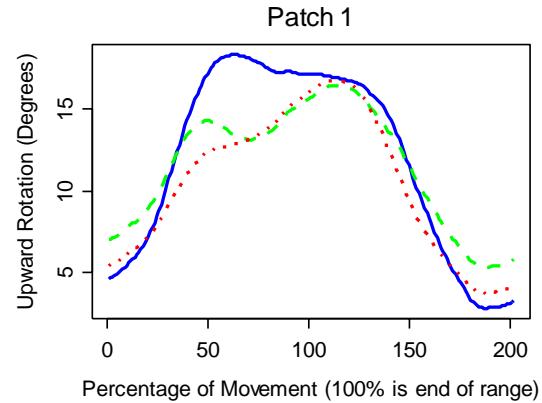
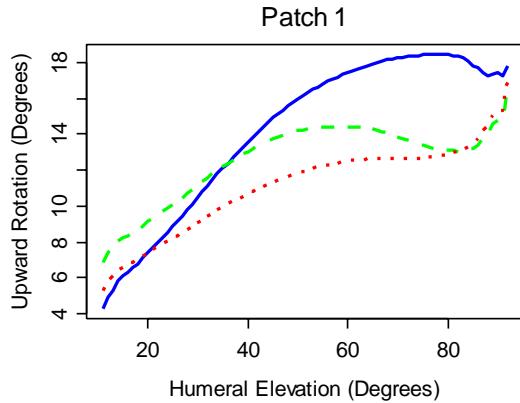
# Reaching: Pins vs. Patches Subject1

## Upward Rotation



## Reaching: Pins vs. Patches Subject2

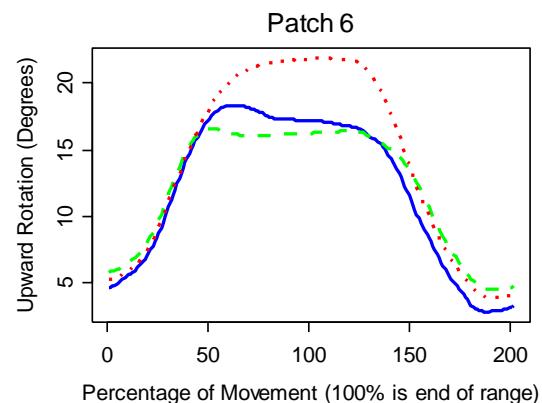
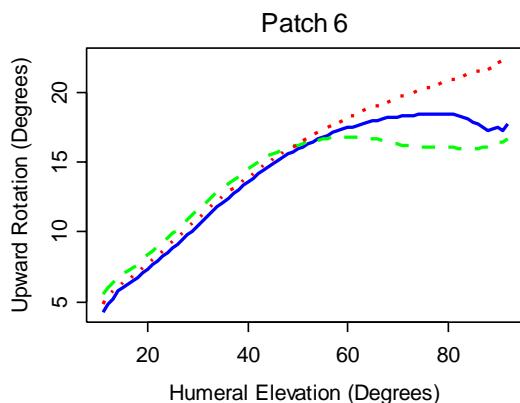
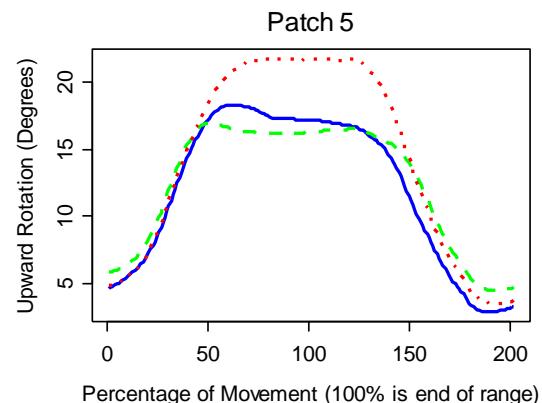
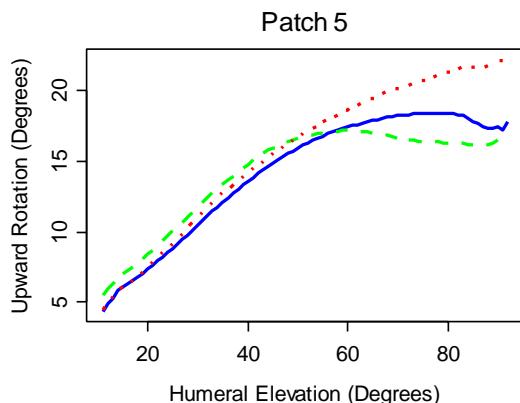
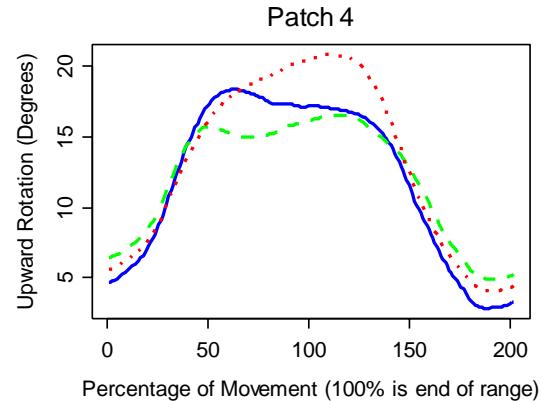
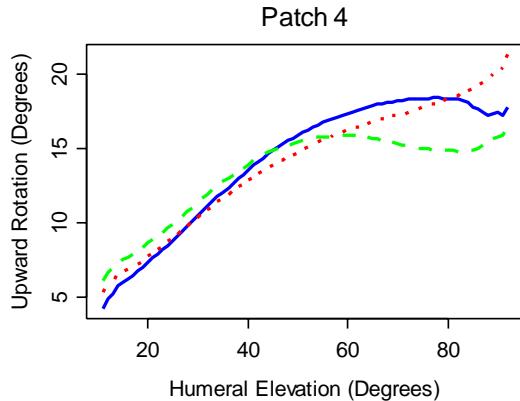
### Upward Rotation



— Pins      - - - Patch Corrected      ··· Patch Uncorrected

## Reaching: Pins vs. Patches Subject2

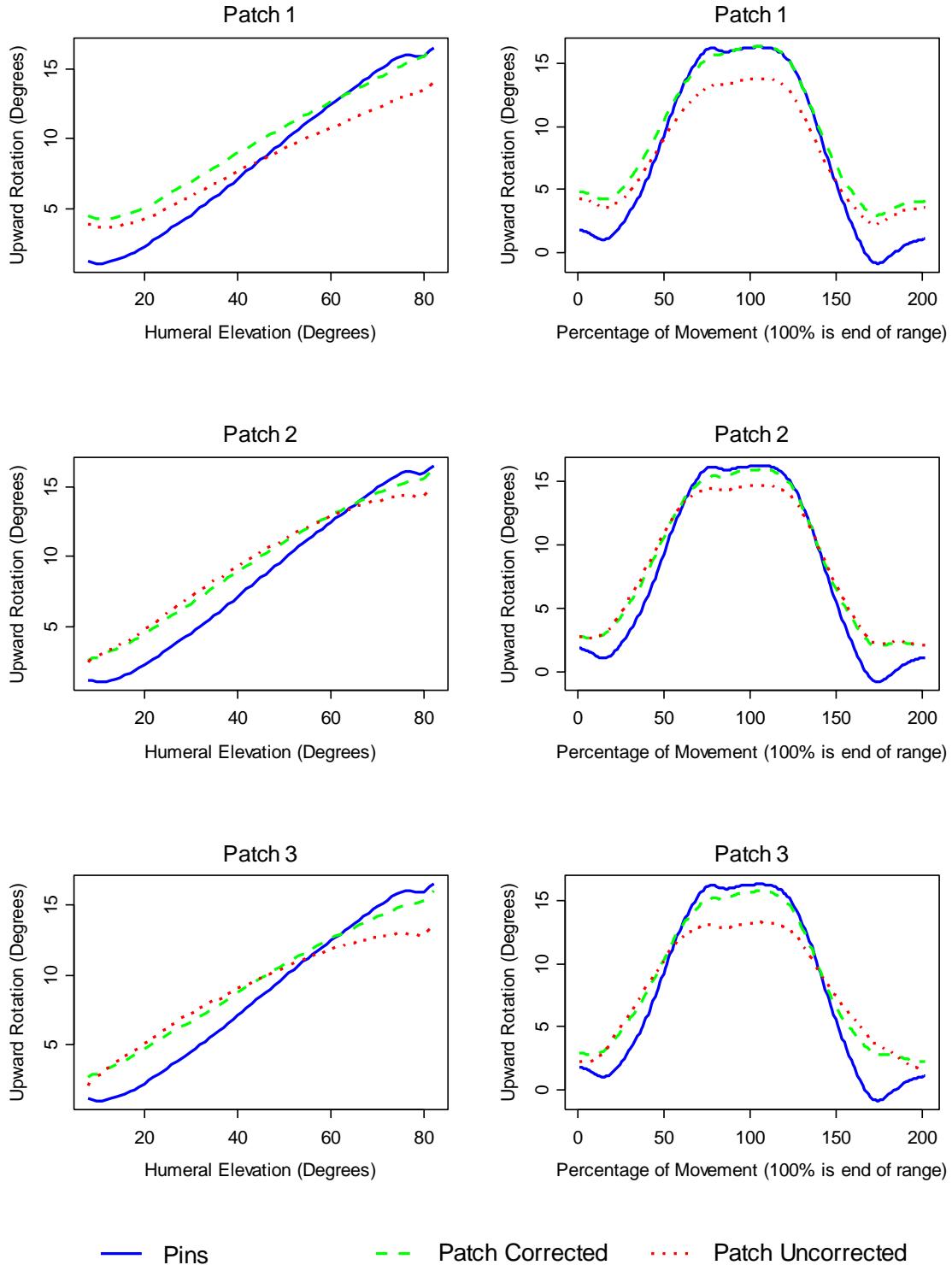
### Upward Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

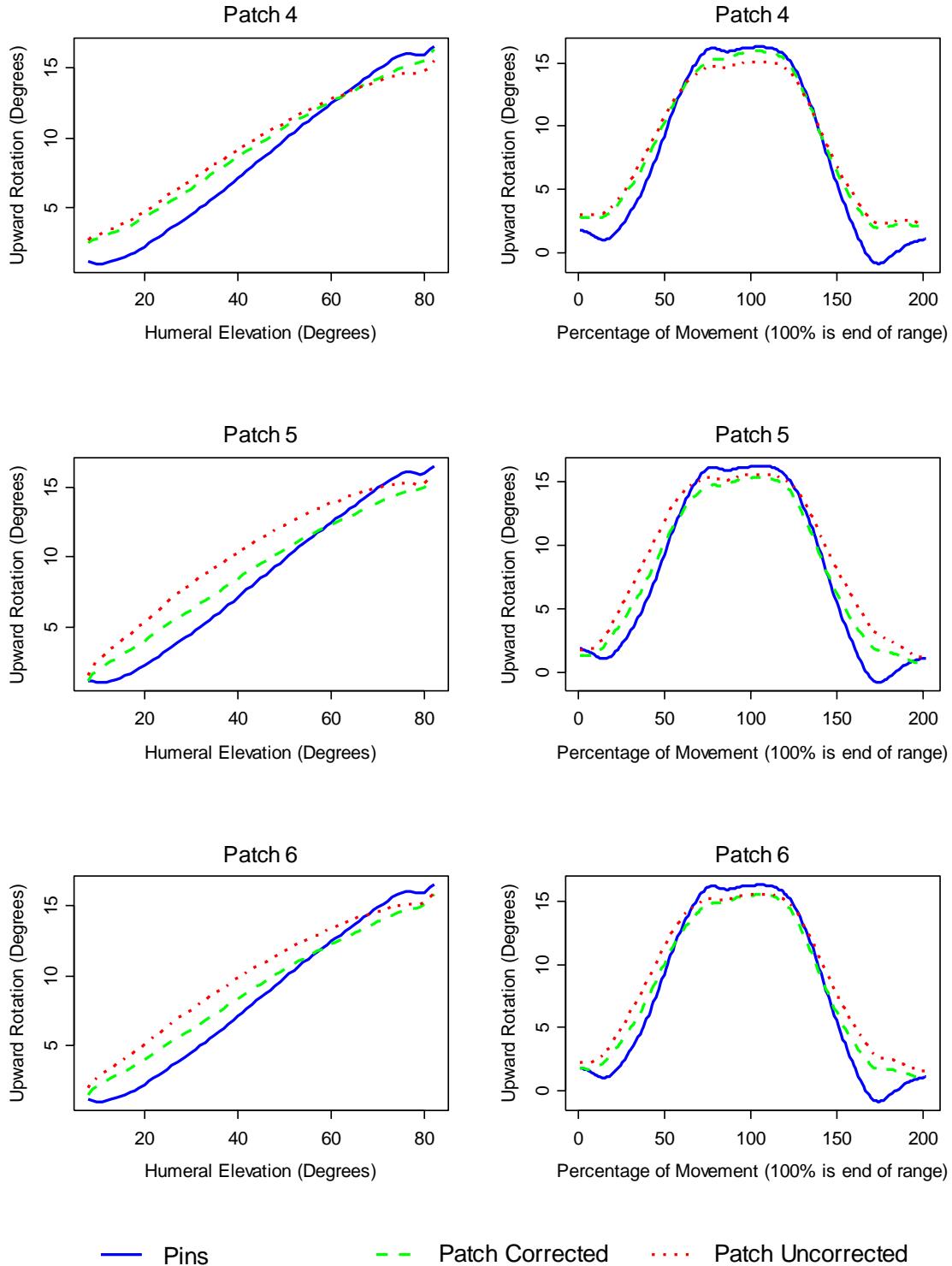
# Reaching: Pins vs. Patches Subject3

## Upward Rotation



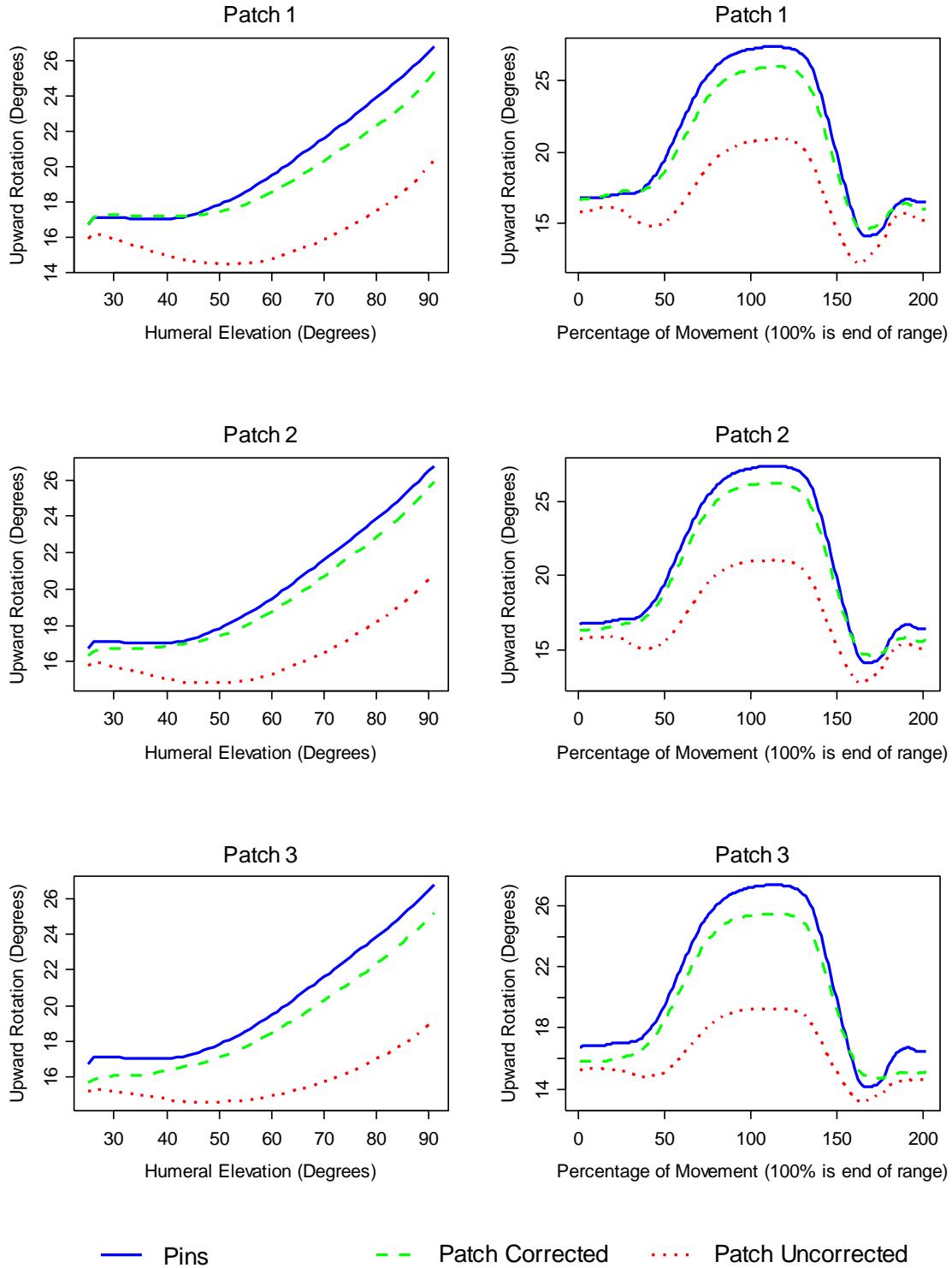
# Reaching: Pins vs. Patches Subject3

## Upward Rotation



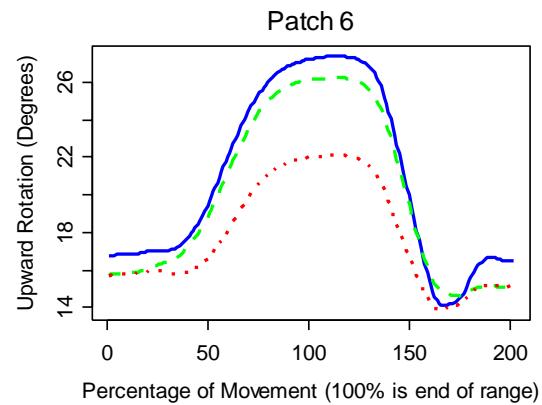
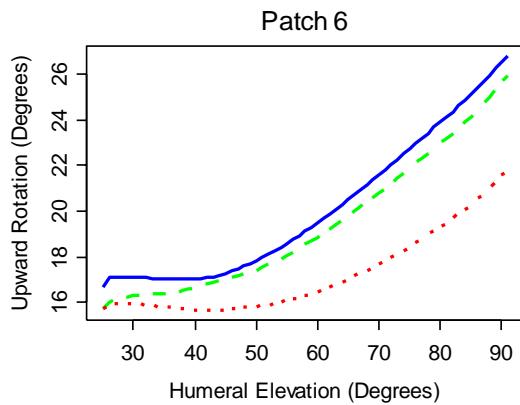
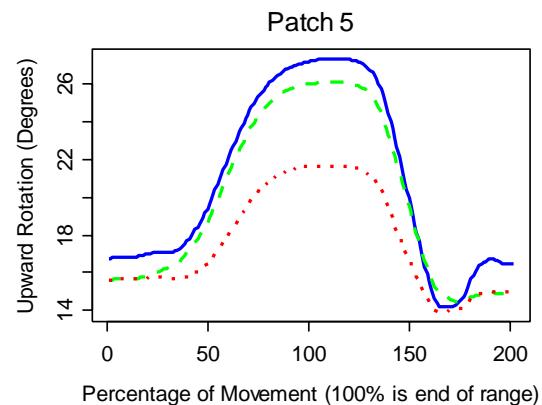
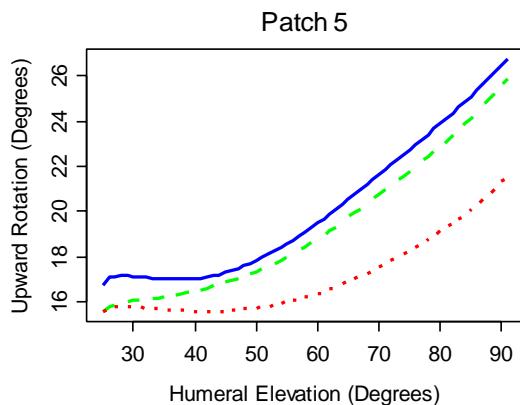
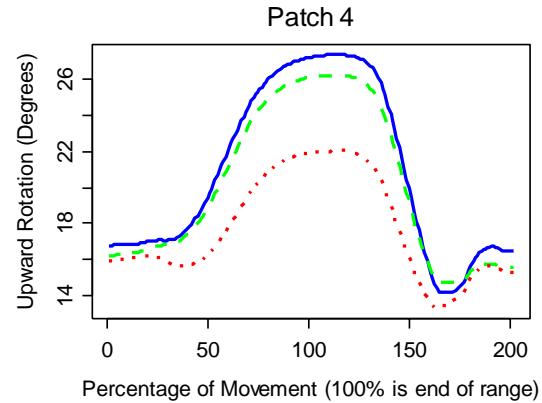
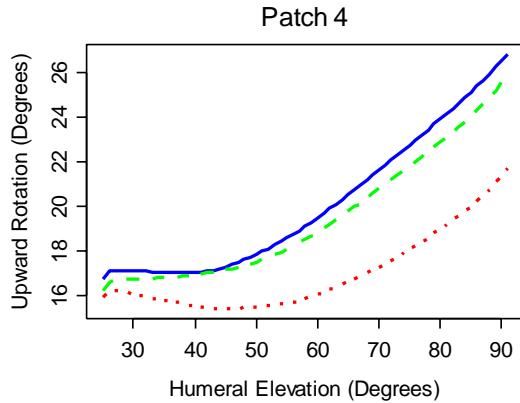
# Reaching: Pins vs. Patches Subject4

## Upward Rotation



# Reaching: Pins vs. Patches Subject4

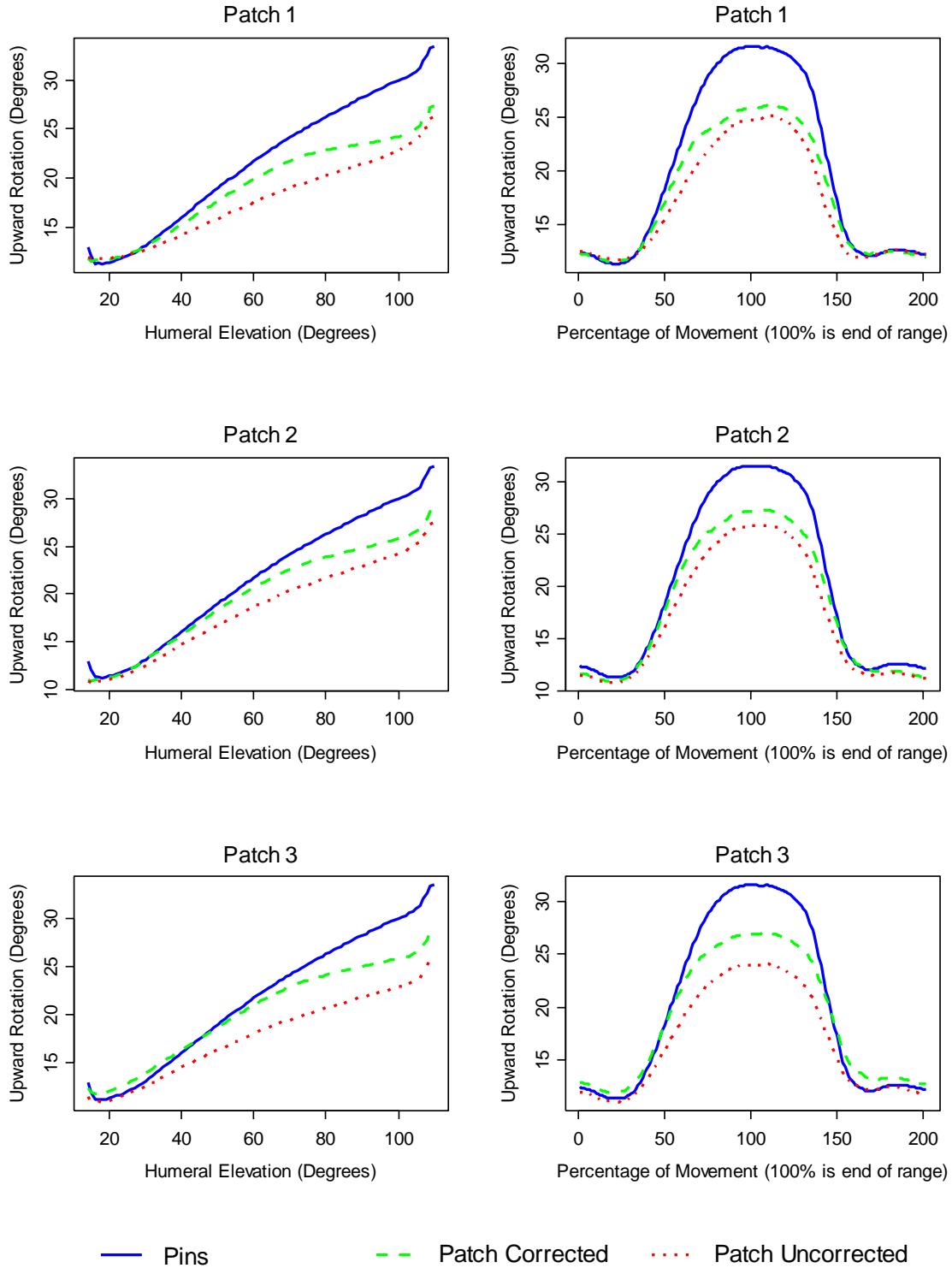
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

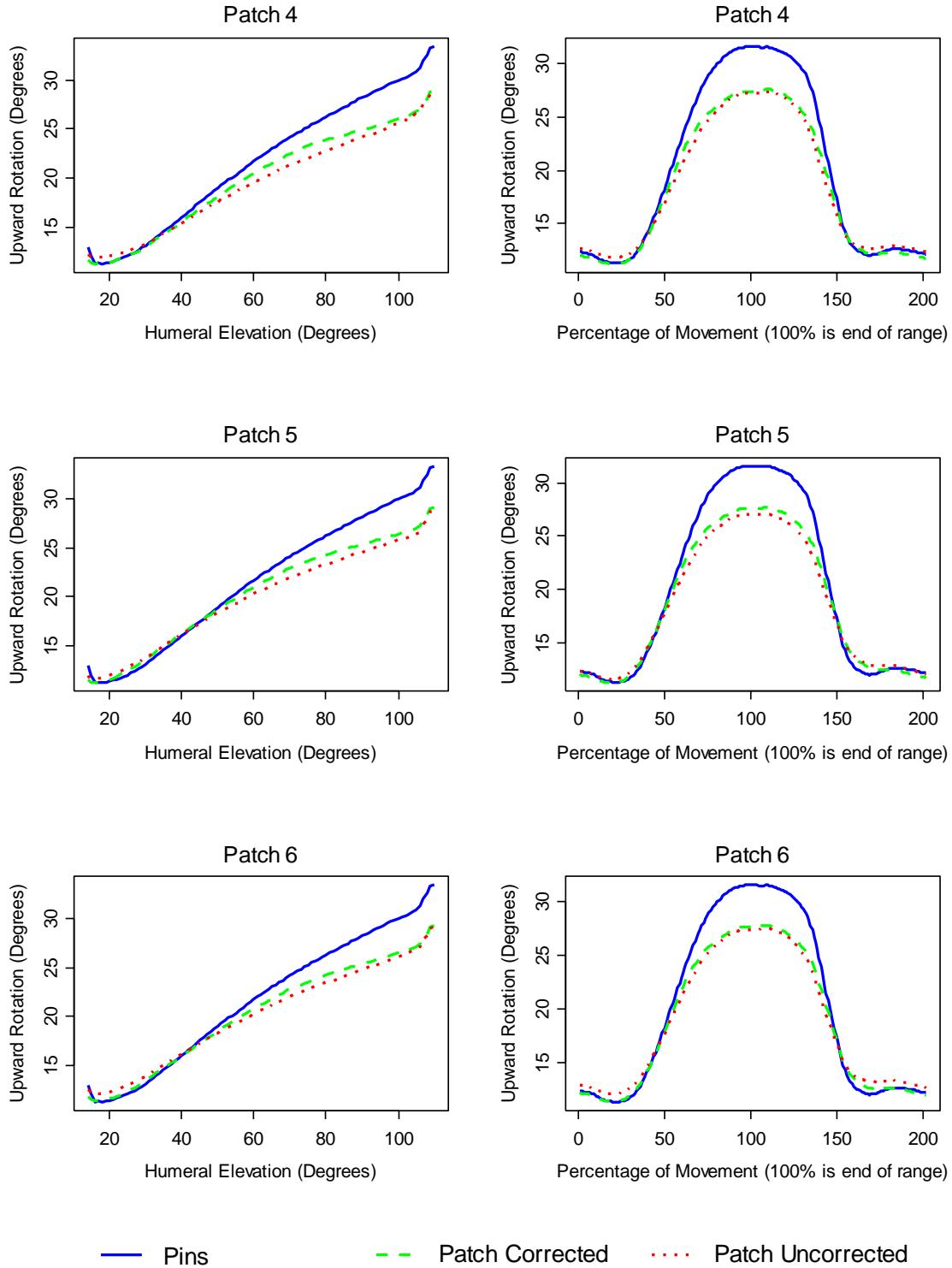
# Reaching: Pins vs. Patches Subject5

## Upward Rotation



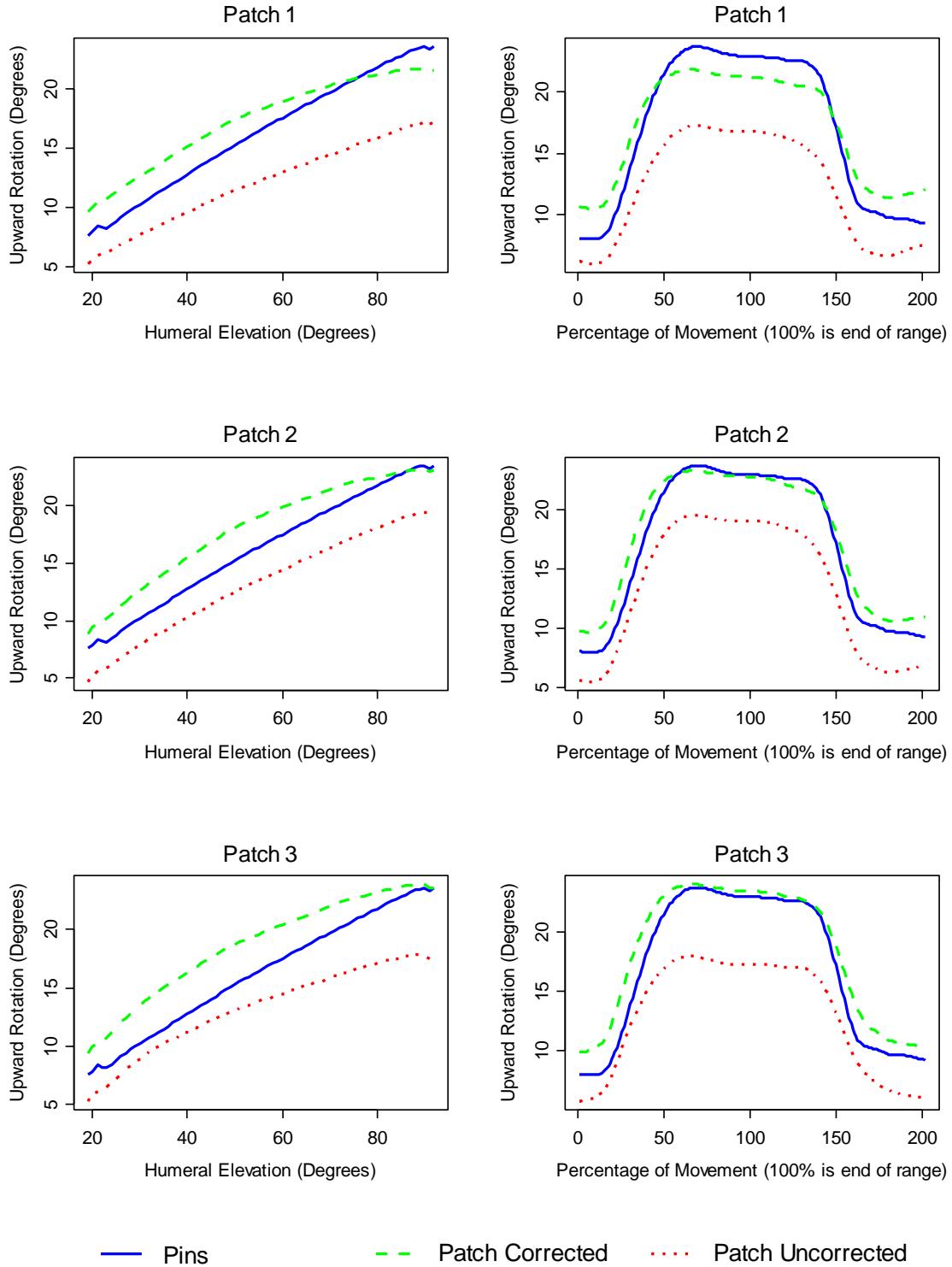
# Reaching: Pins vs. Patches Subject5

## Upward Rotation



# Reaching: Pins vs. Patches Subject6

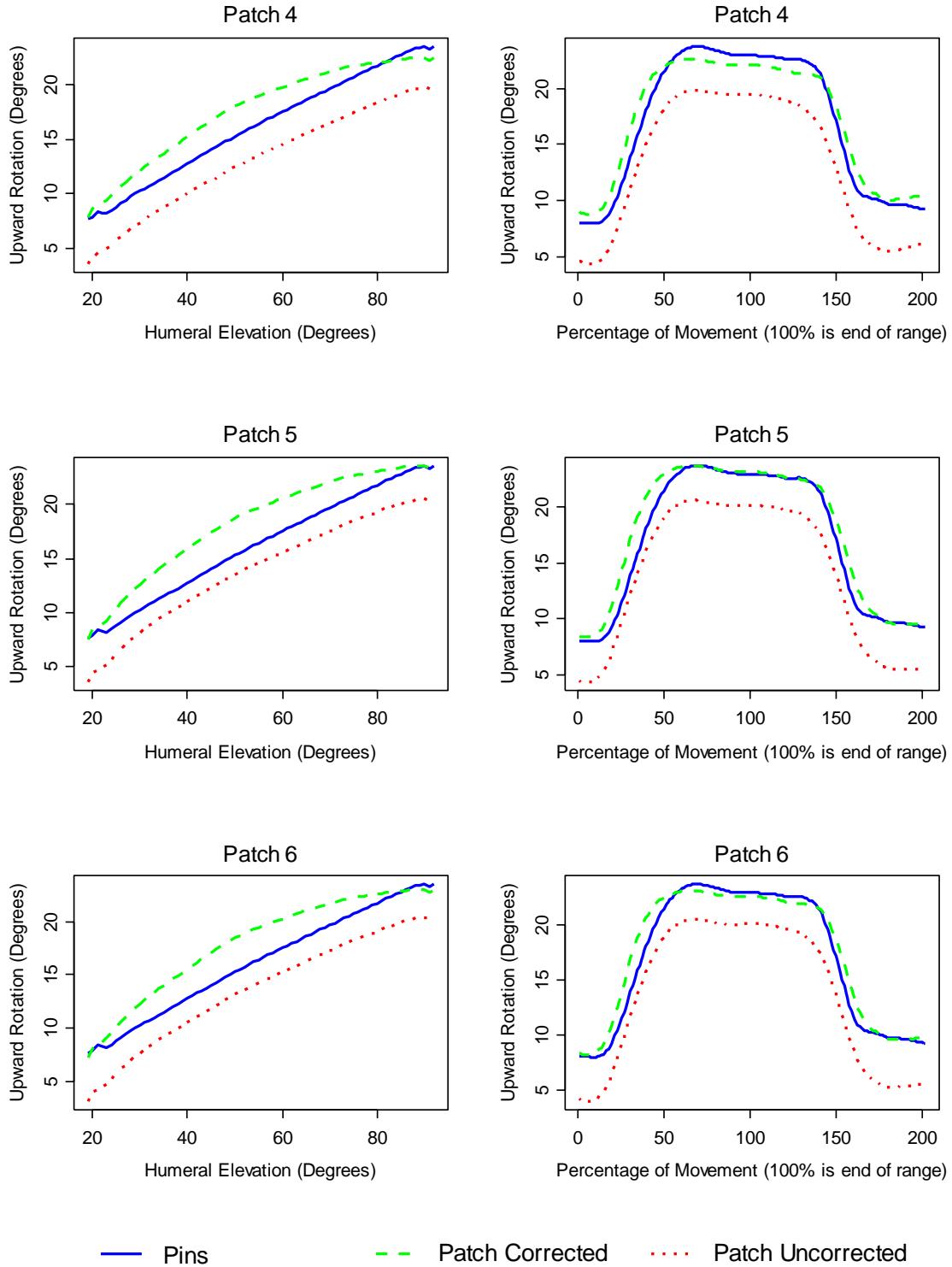
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

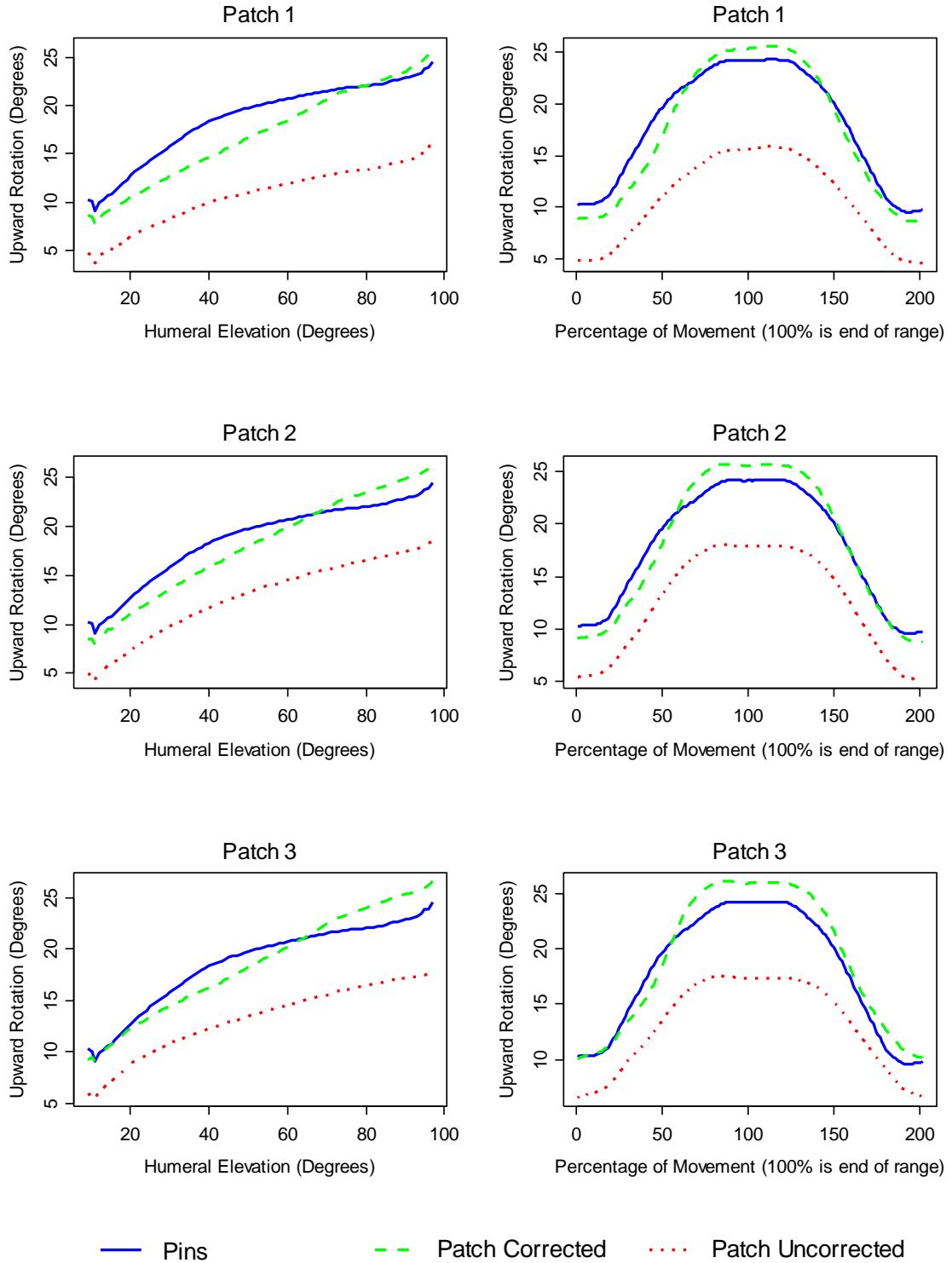
# Reaching: Pins vs. Patches Subject6

## Upward Rotation



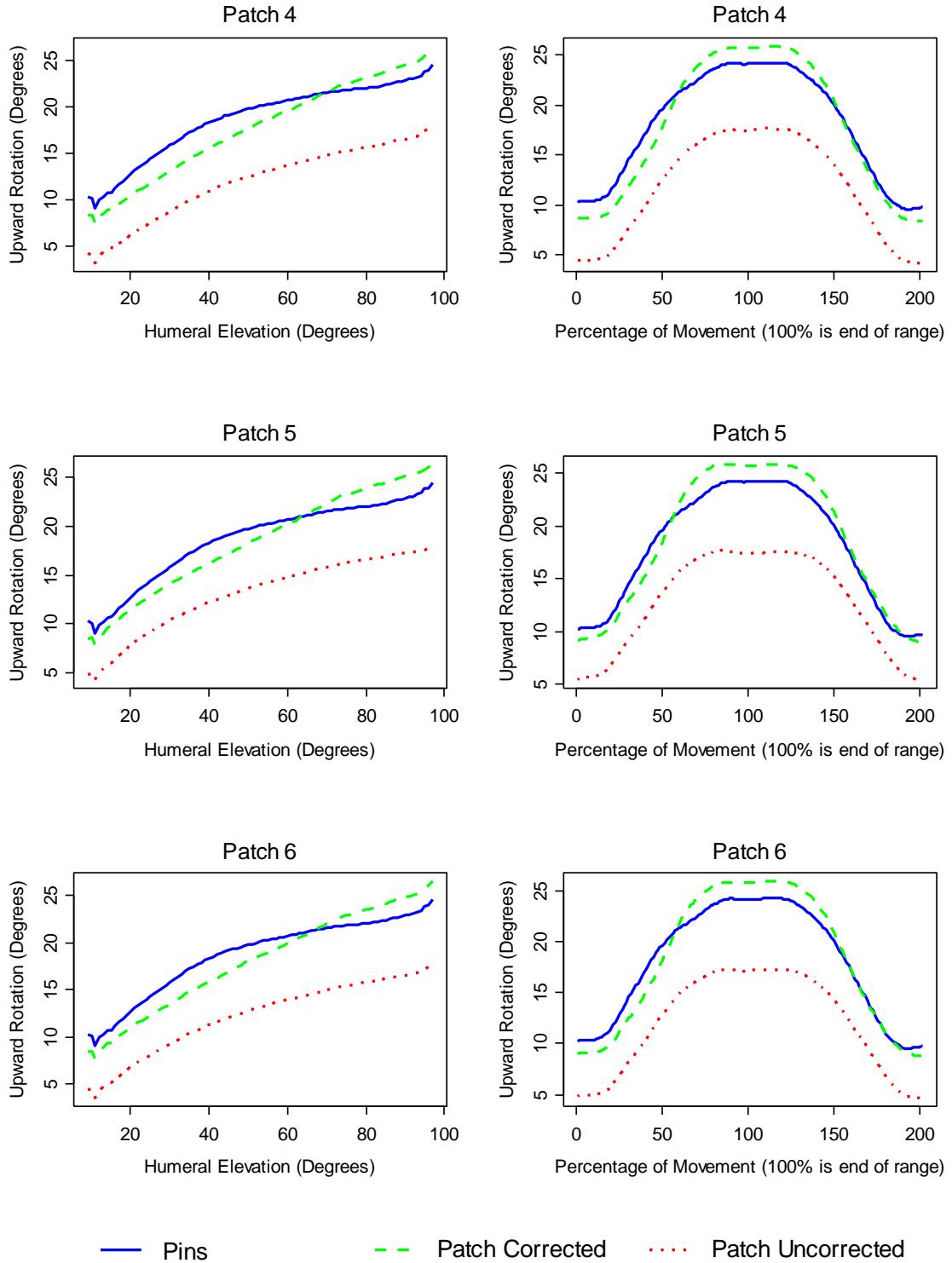
# Reaching: Pins vs. Patches Subject7

## Upward Rotation



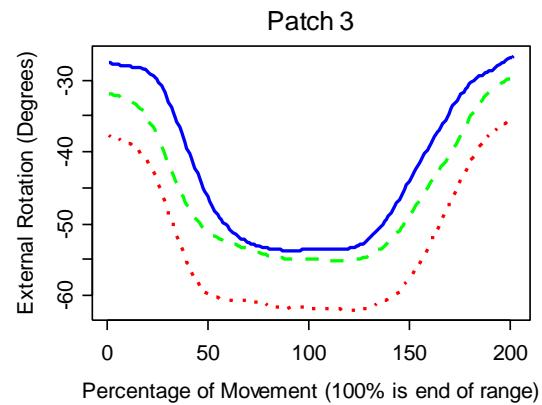
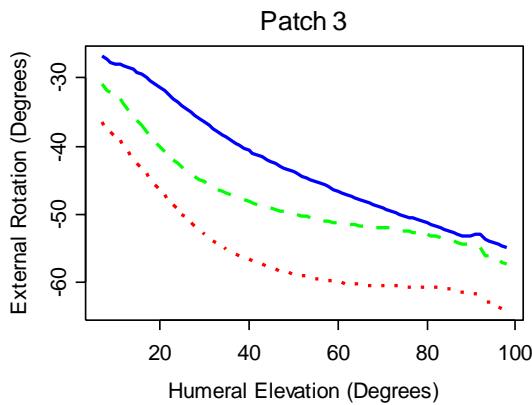
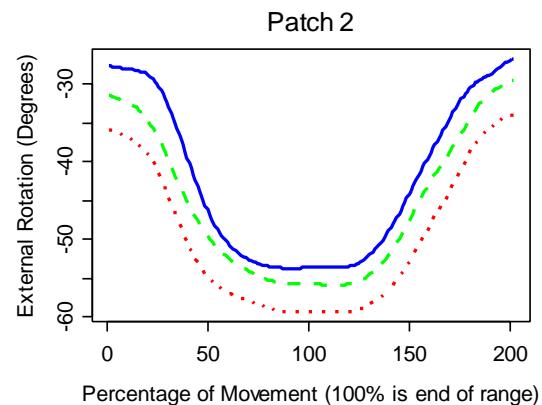
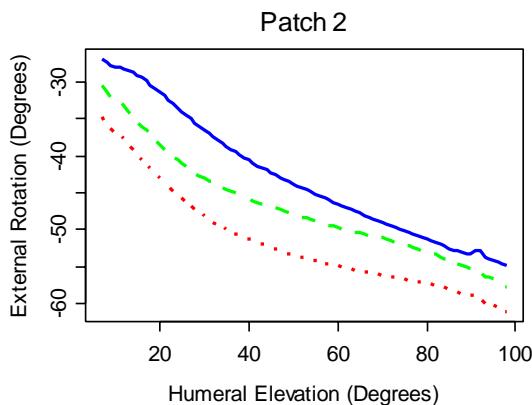
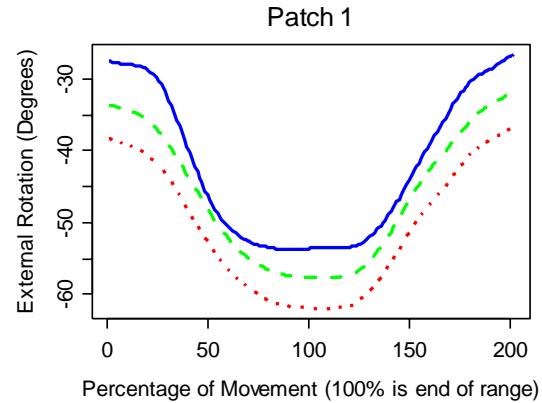
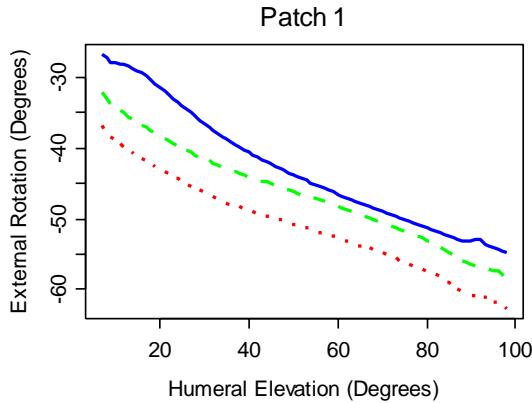
# Reaching: Pins vs. Patches Subject7

## Upward Rotation



# Reaching: Pins vs. Patches Subject1

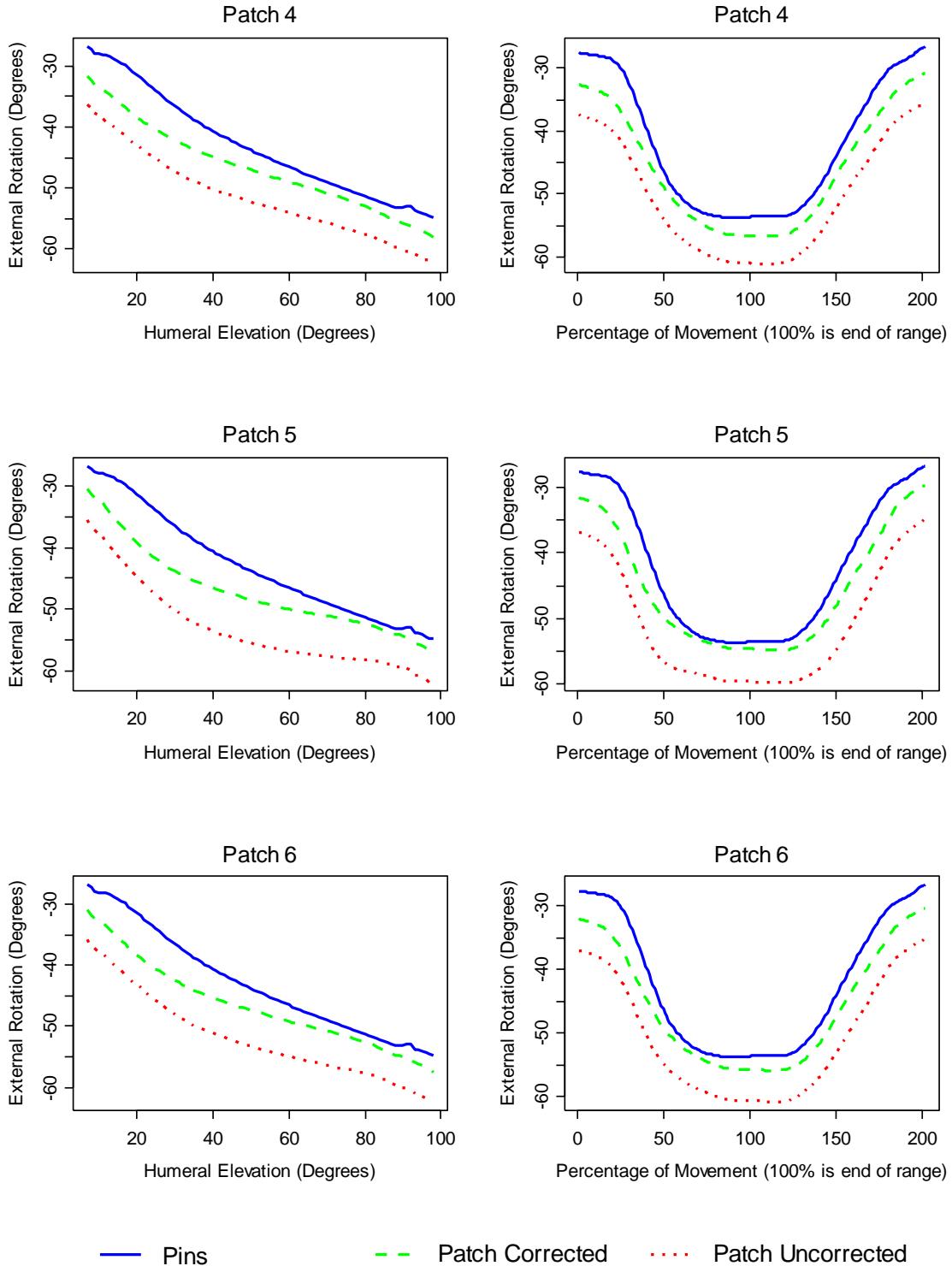
## External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

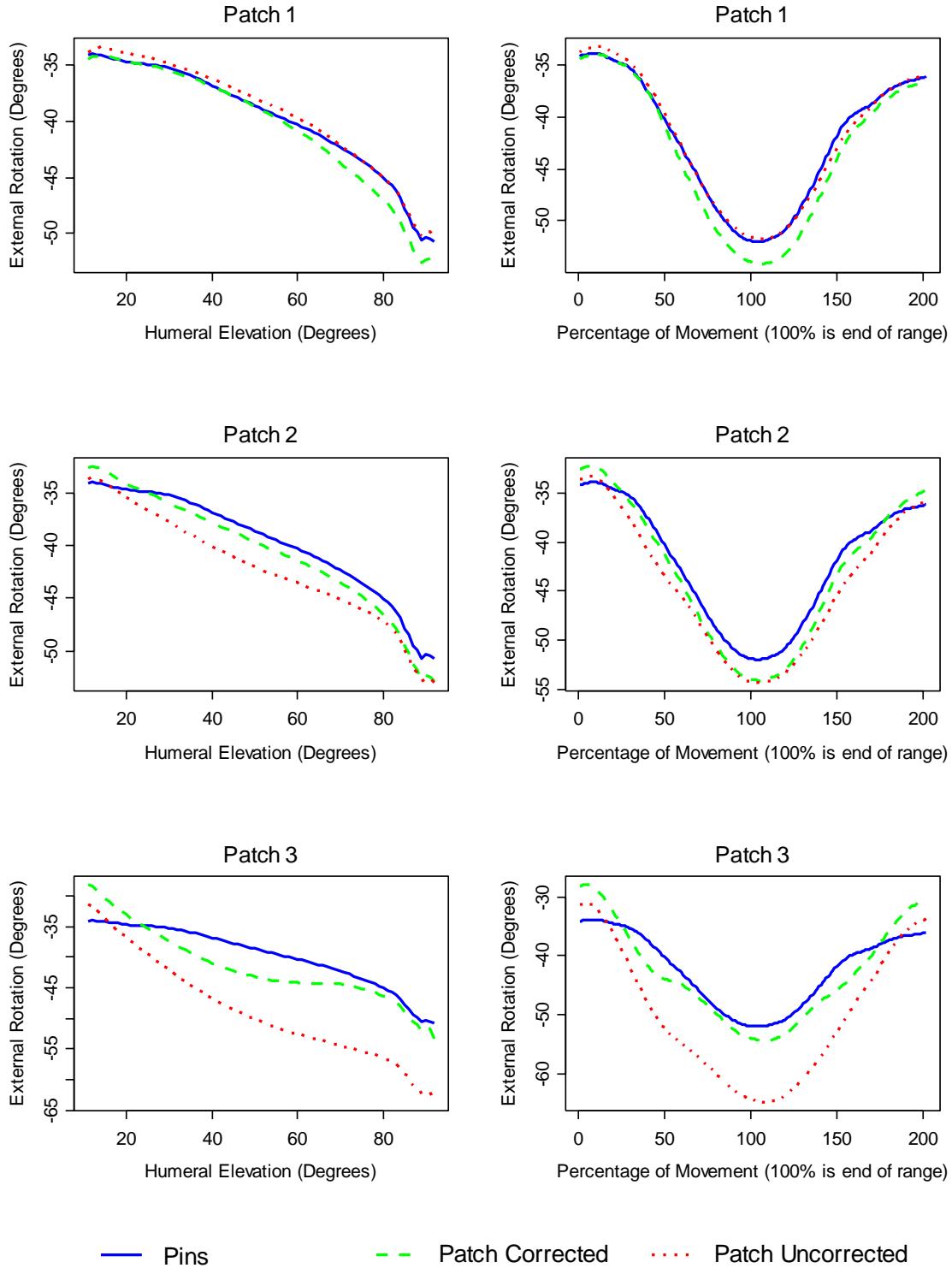
## Reaching: Pins vs. Patches Subject1

### External Rotation



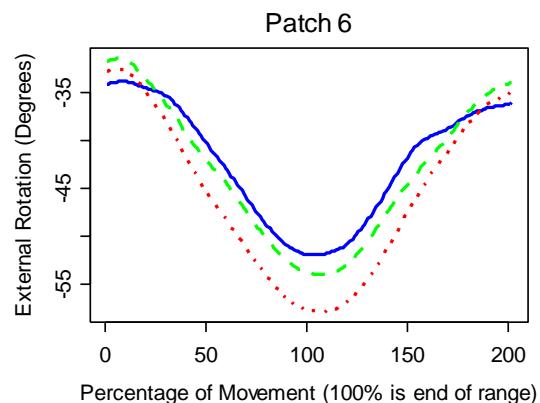
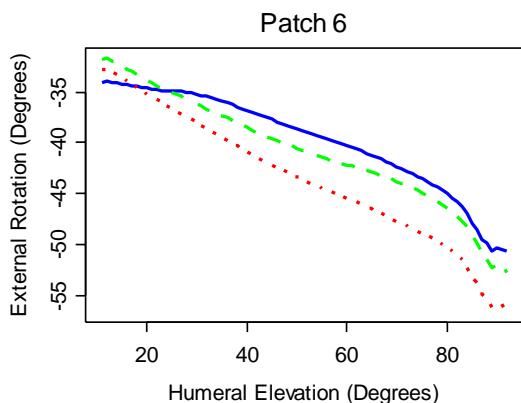
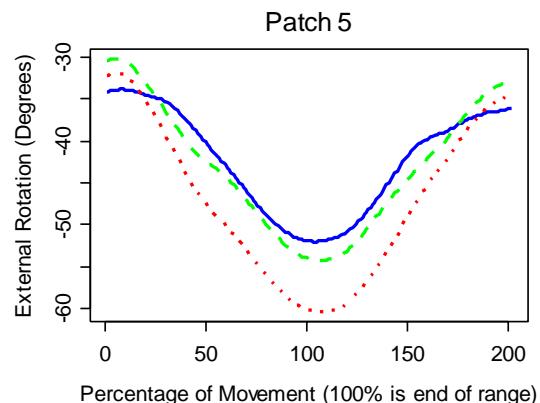
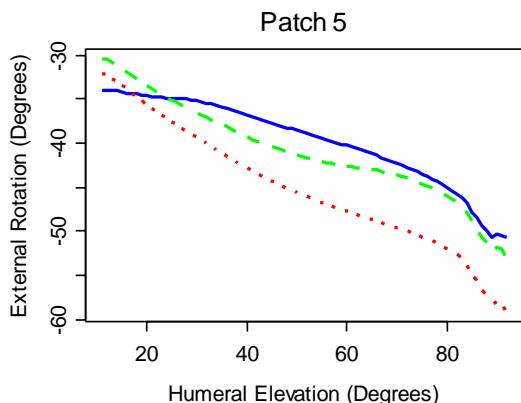
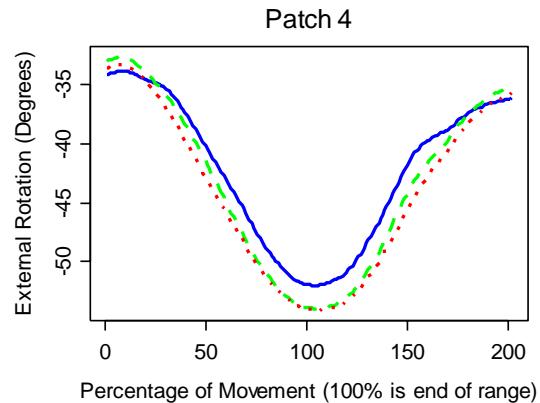
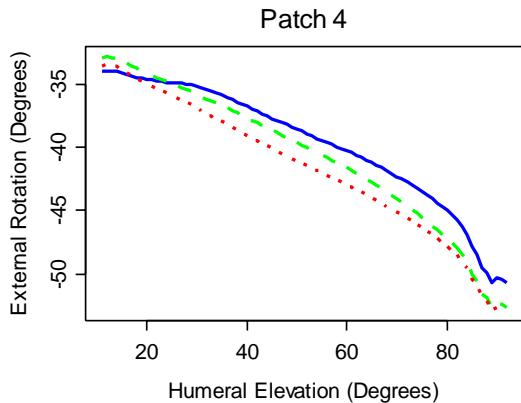
## Reaching: Pins vs. Patches Subject2

### External Rotation



## Reaching: Pins vs. Patches Subject2

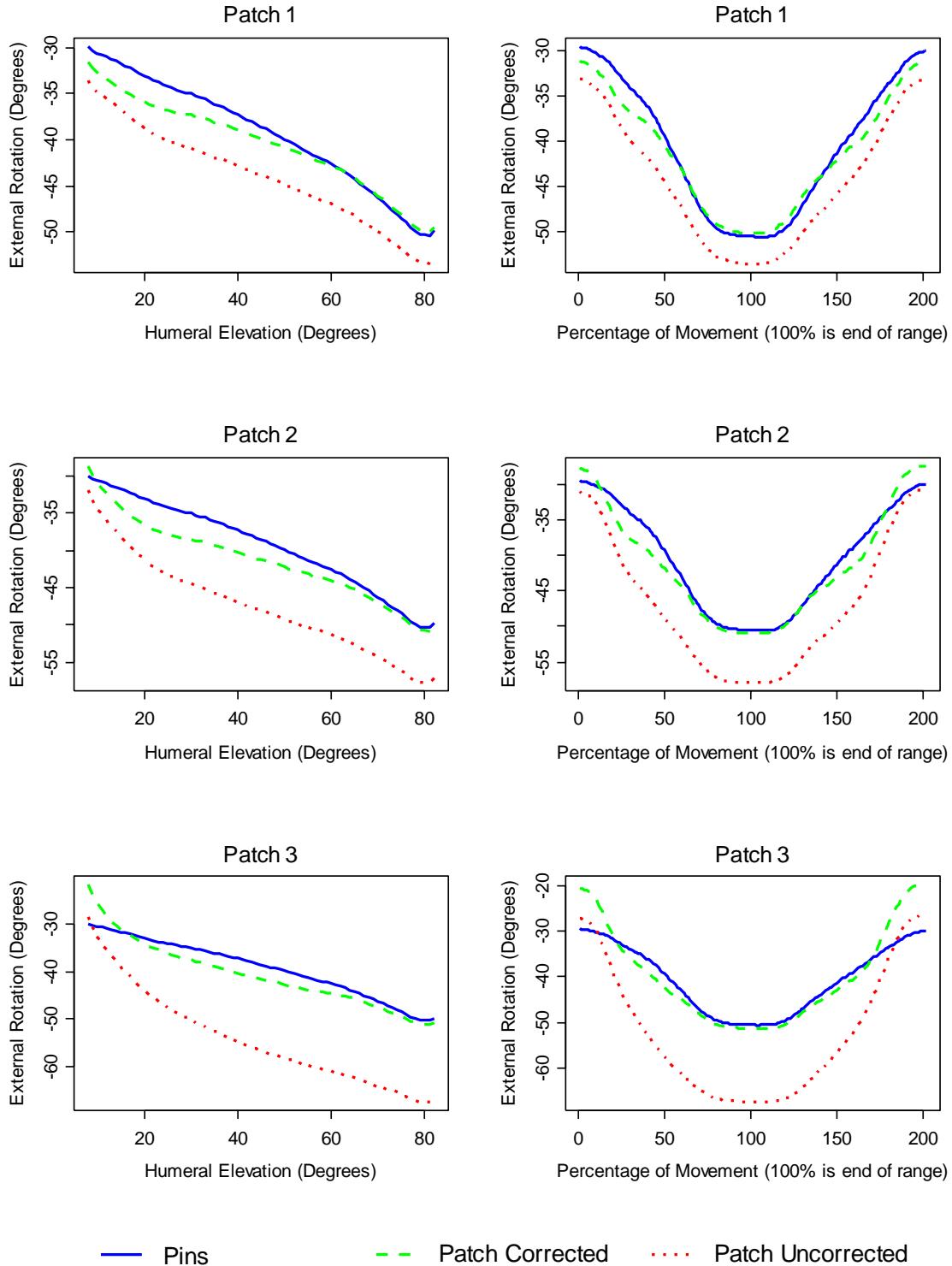
### External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

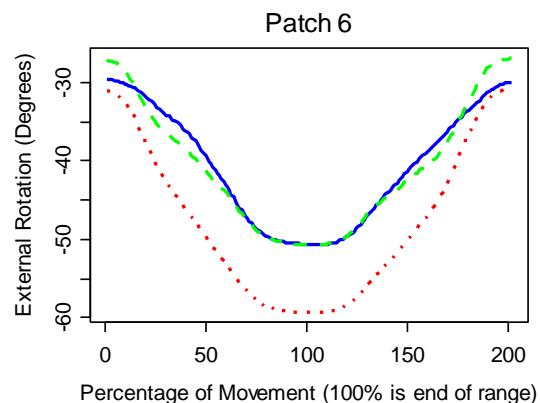
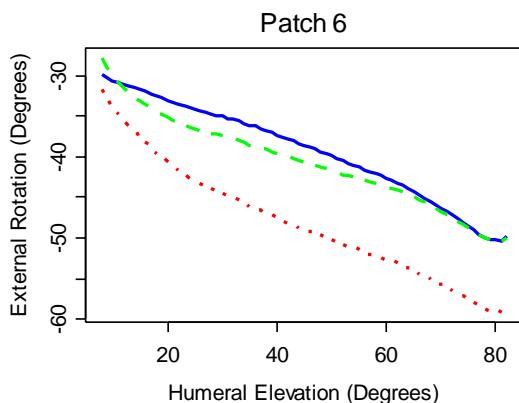
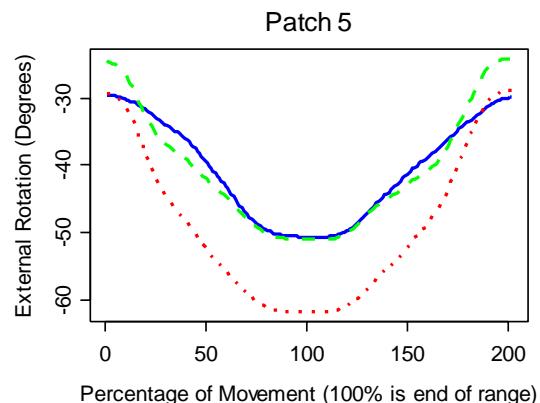
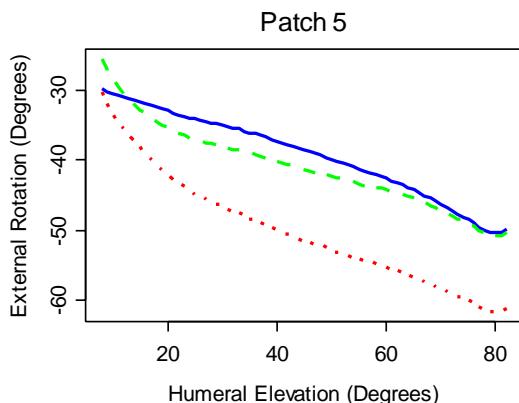
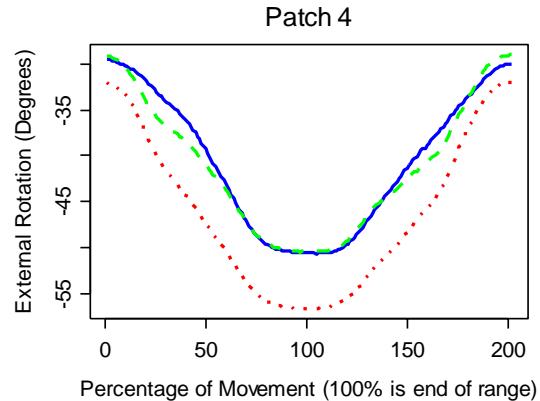
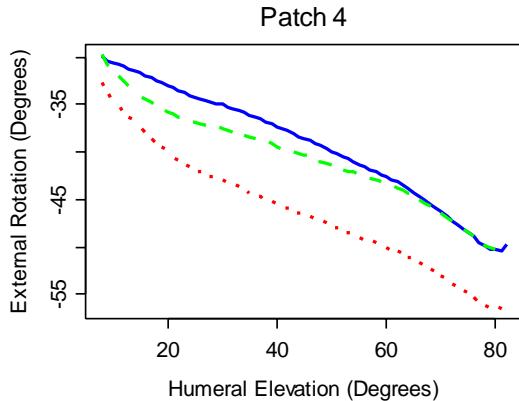
# Reaching: Pins vs. Patches Subject3

## External Rotation



## Reaching: Pins vs. Patches Subject3

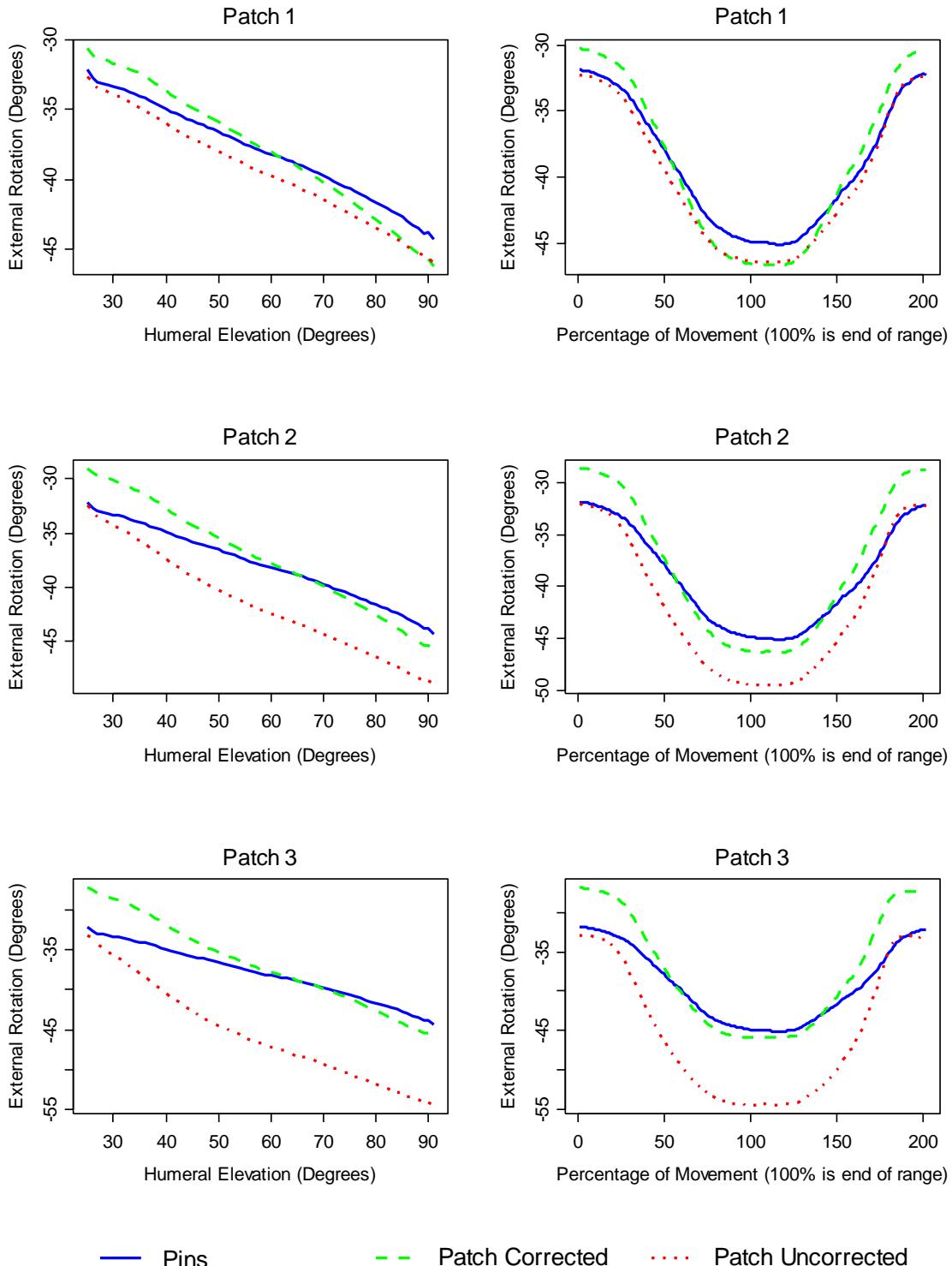
### External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

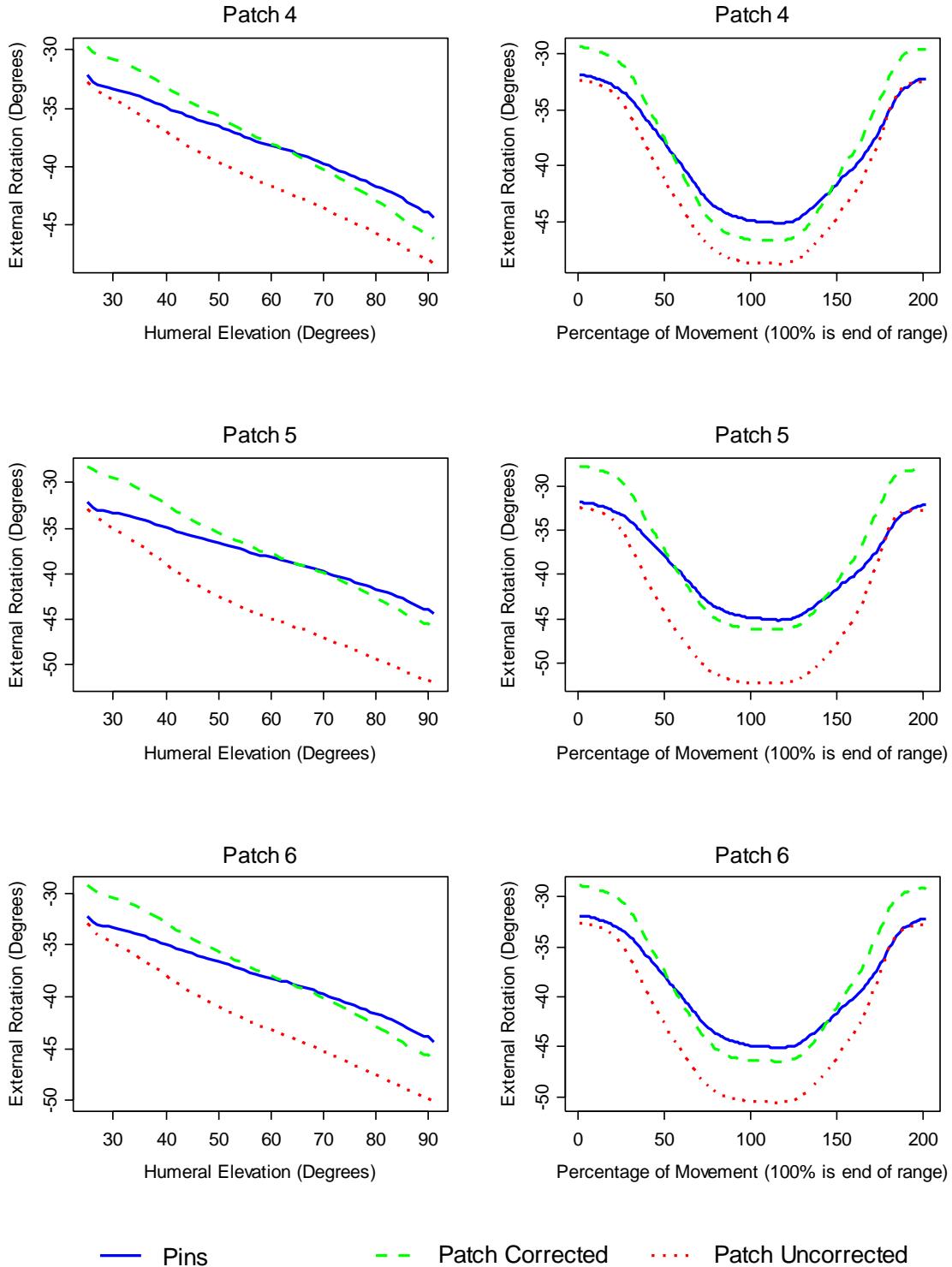
## Reaching: Pins vs. Patches Subject4

### External Rotation



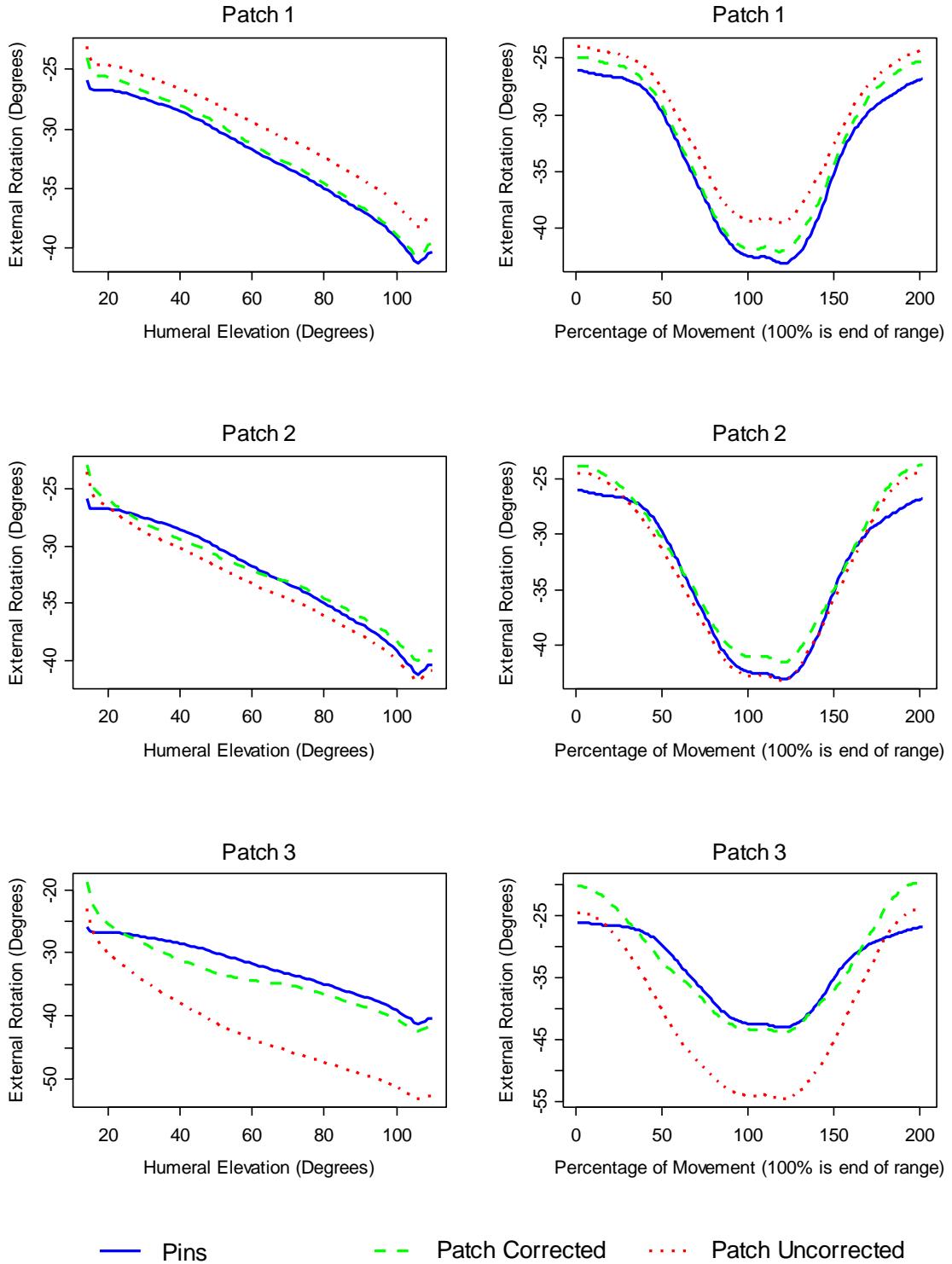
## Reaching: Pins vs. Patches Subject4

### External Rotation



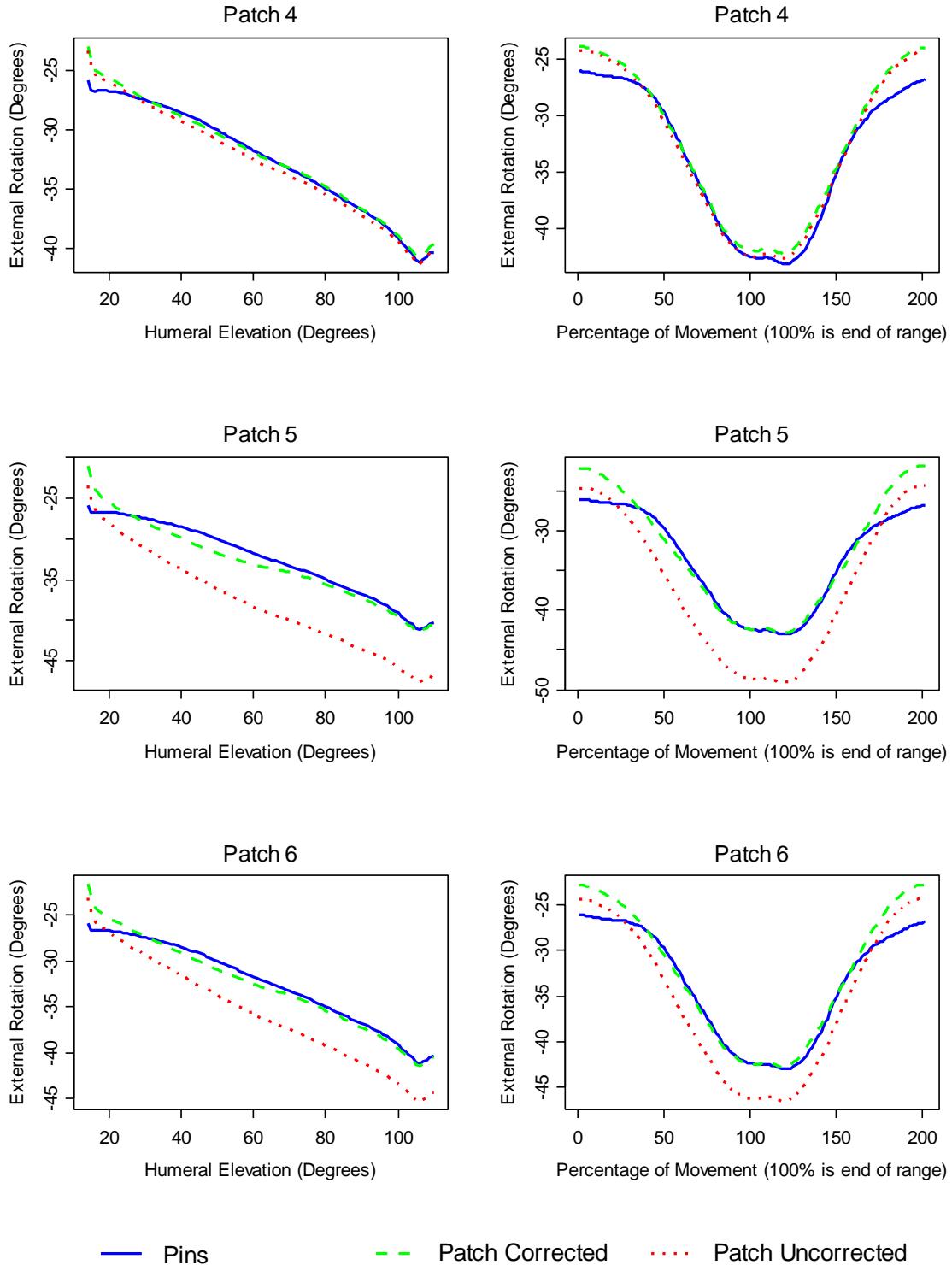
# Reaching: Pins vs. Patches Subject5

## External Rotation



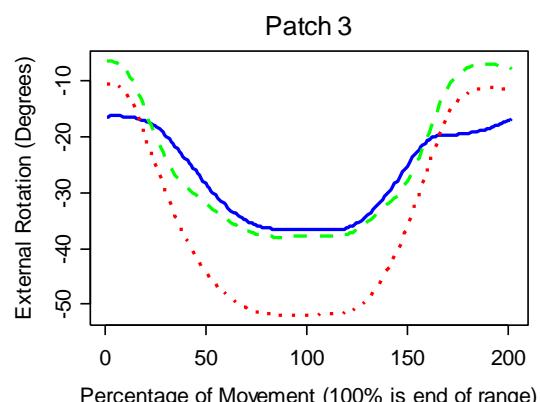
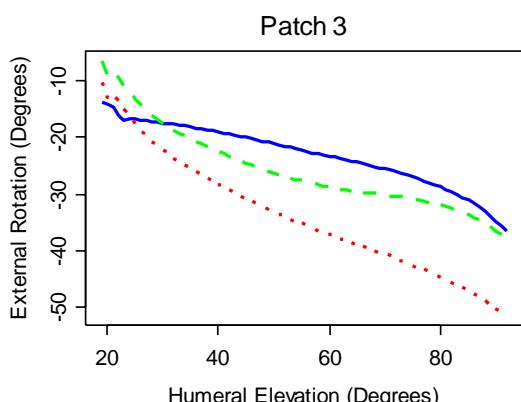
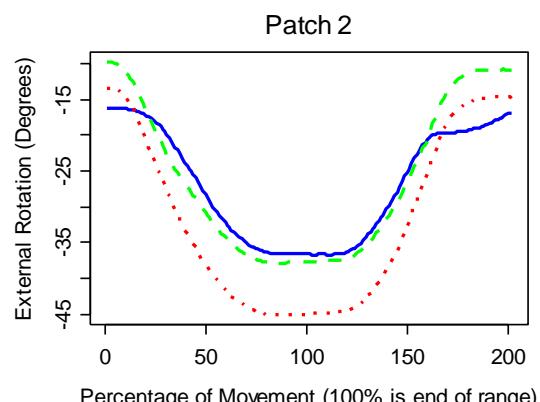
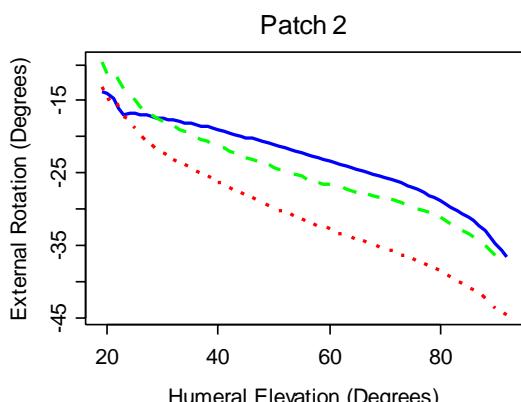
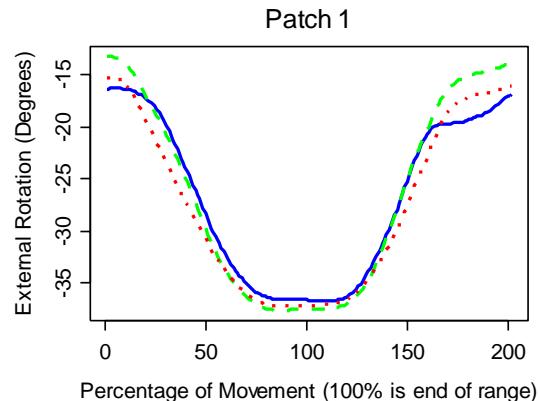
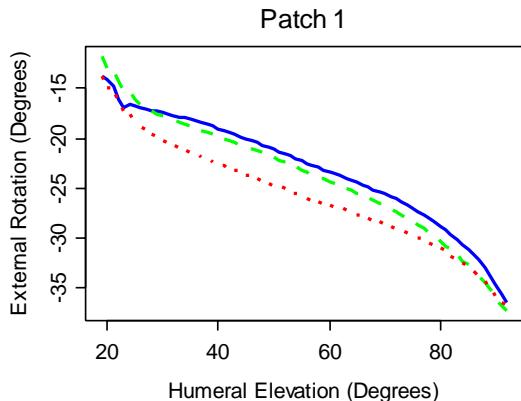
# Reaching: Pins vs. Patches Subject5

## External Rotation



## Reaching: Pins vs. Patches Subject6

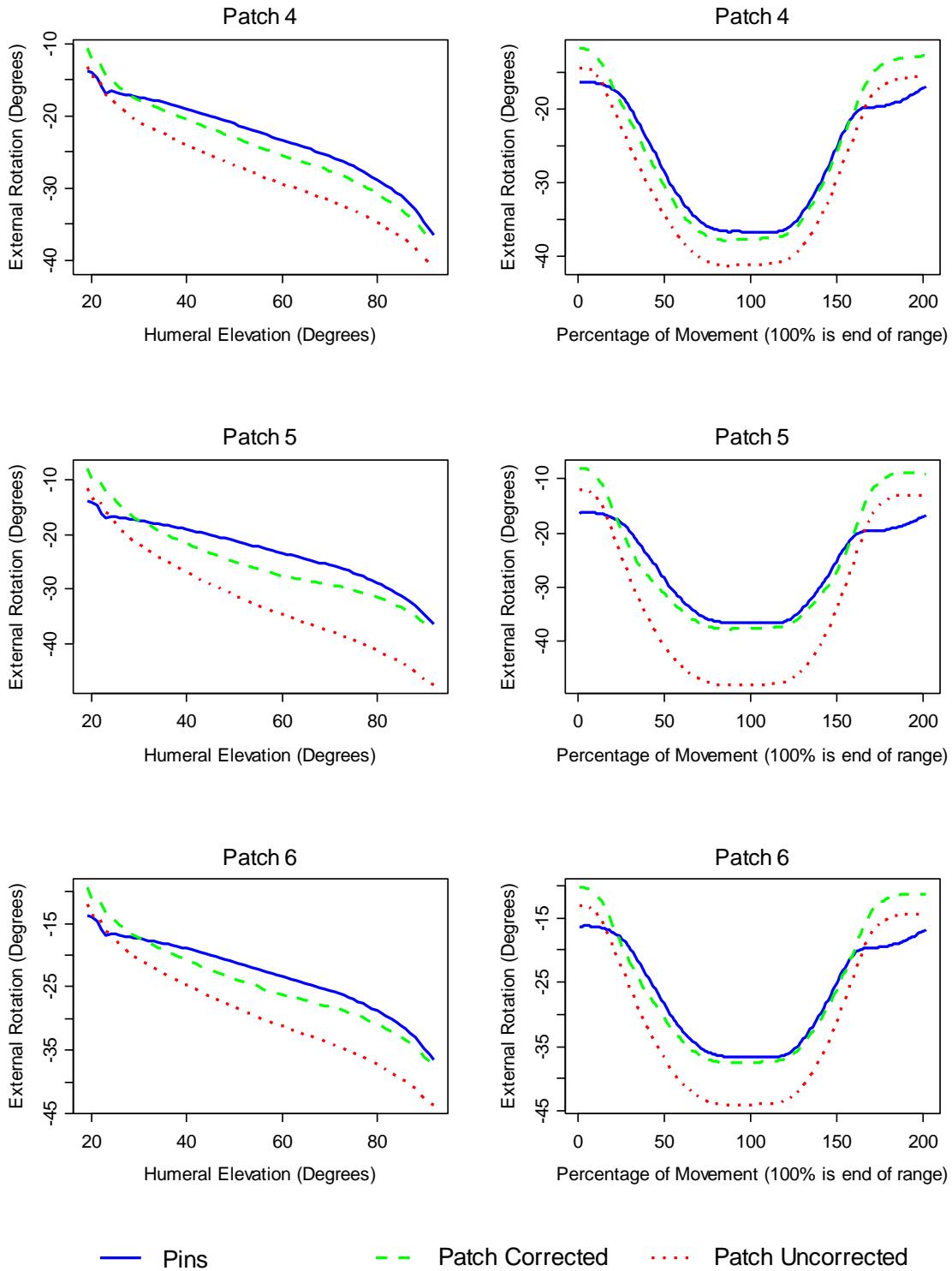
### External Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

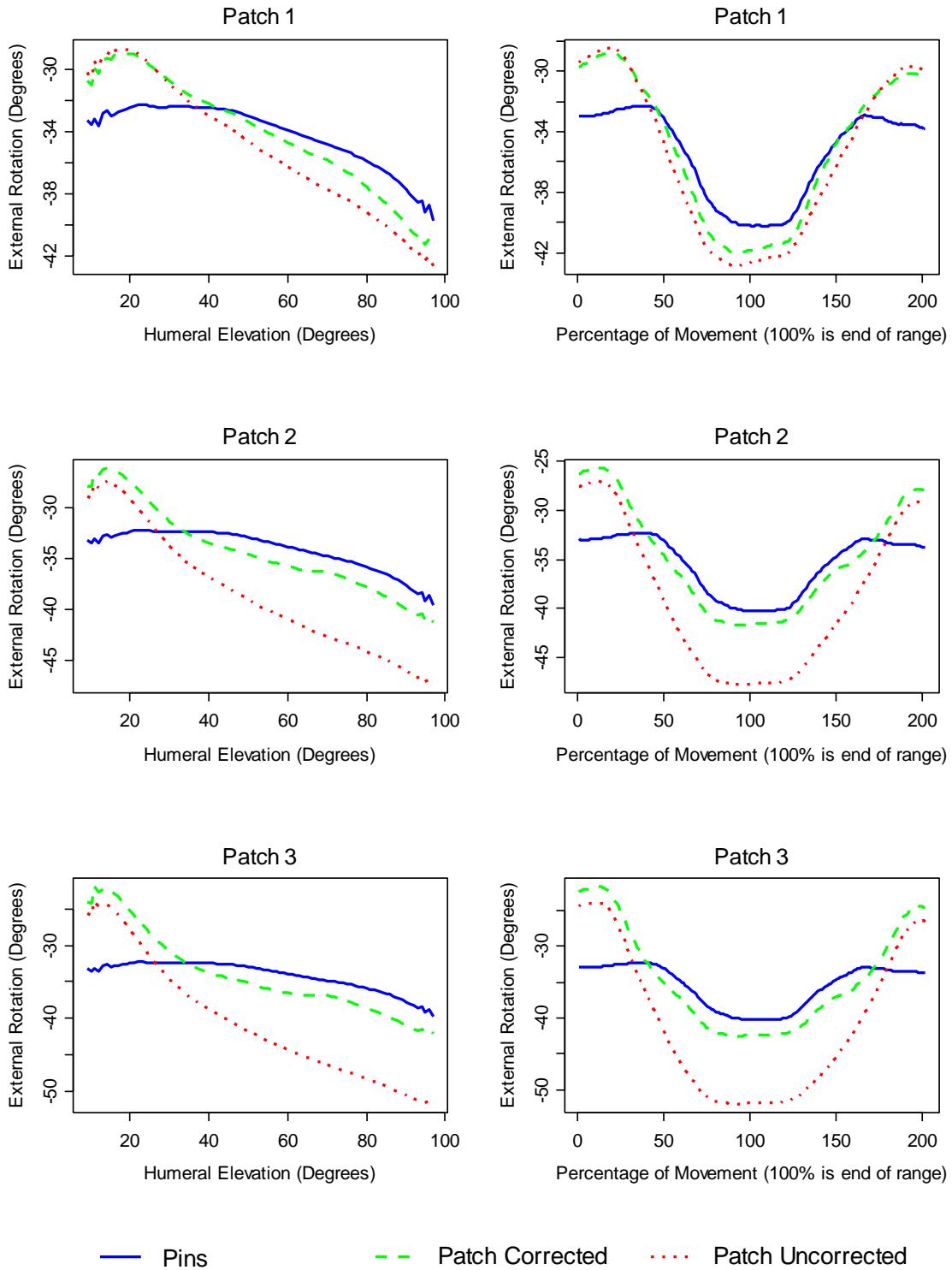
## Reaching: Pins vs. Patches Subject6

### External Rotation



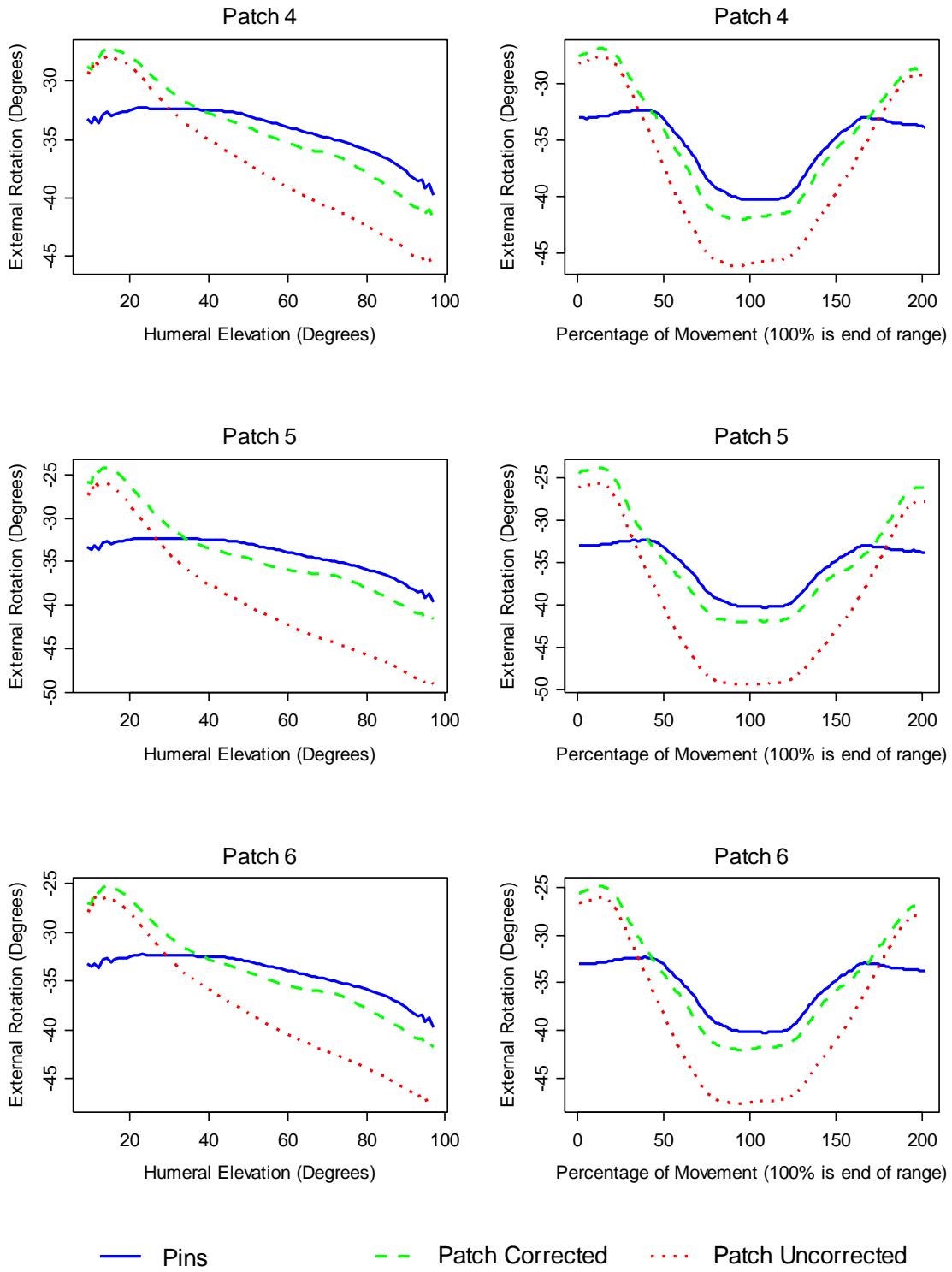
## Reaching: Pins vs. Patches Subject7

### External Rotation



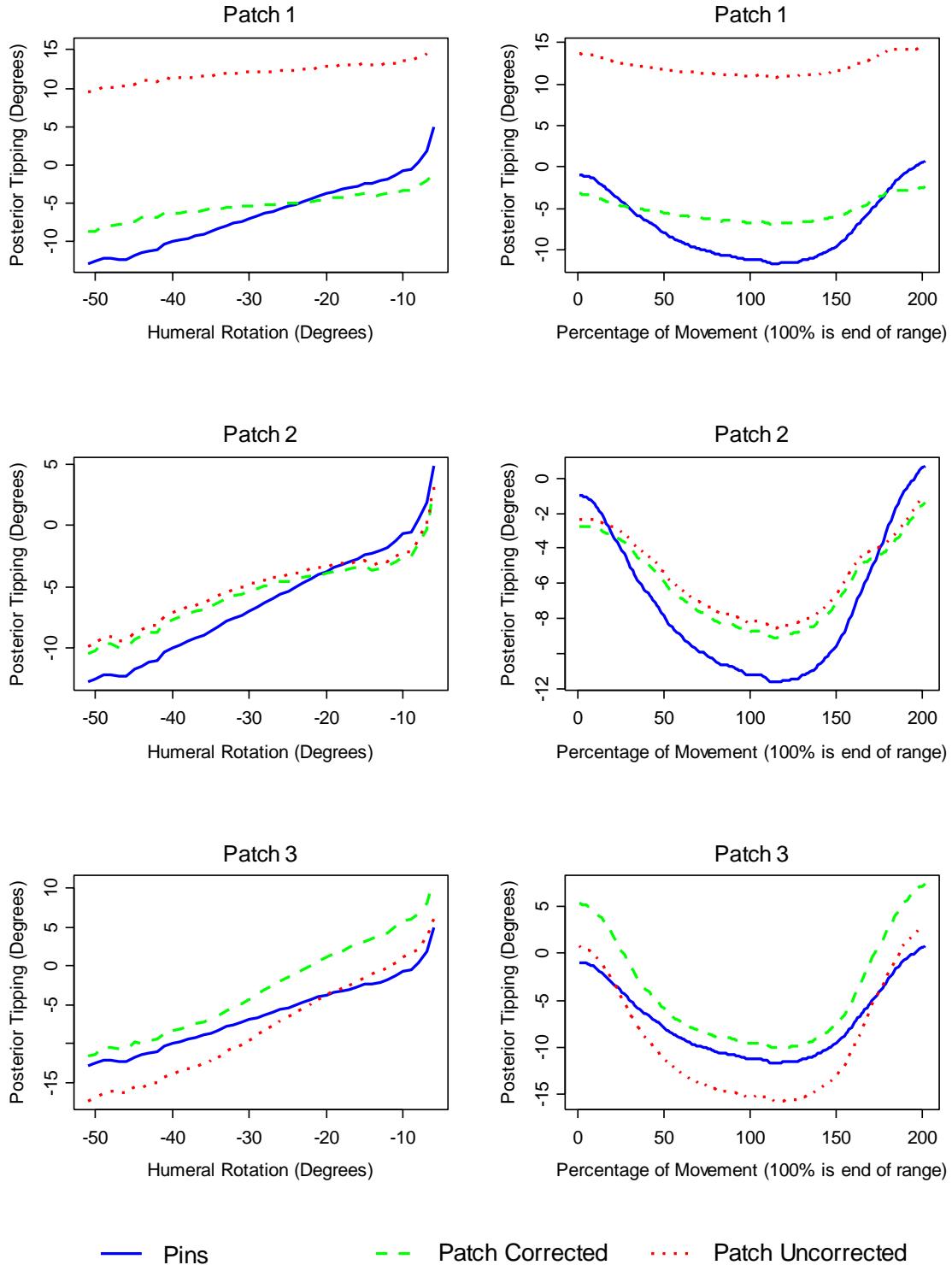
## Reaching: Pins vs. Patches Subject7

### External Rotation



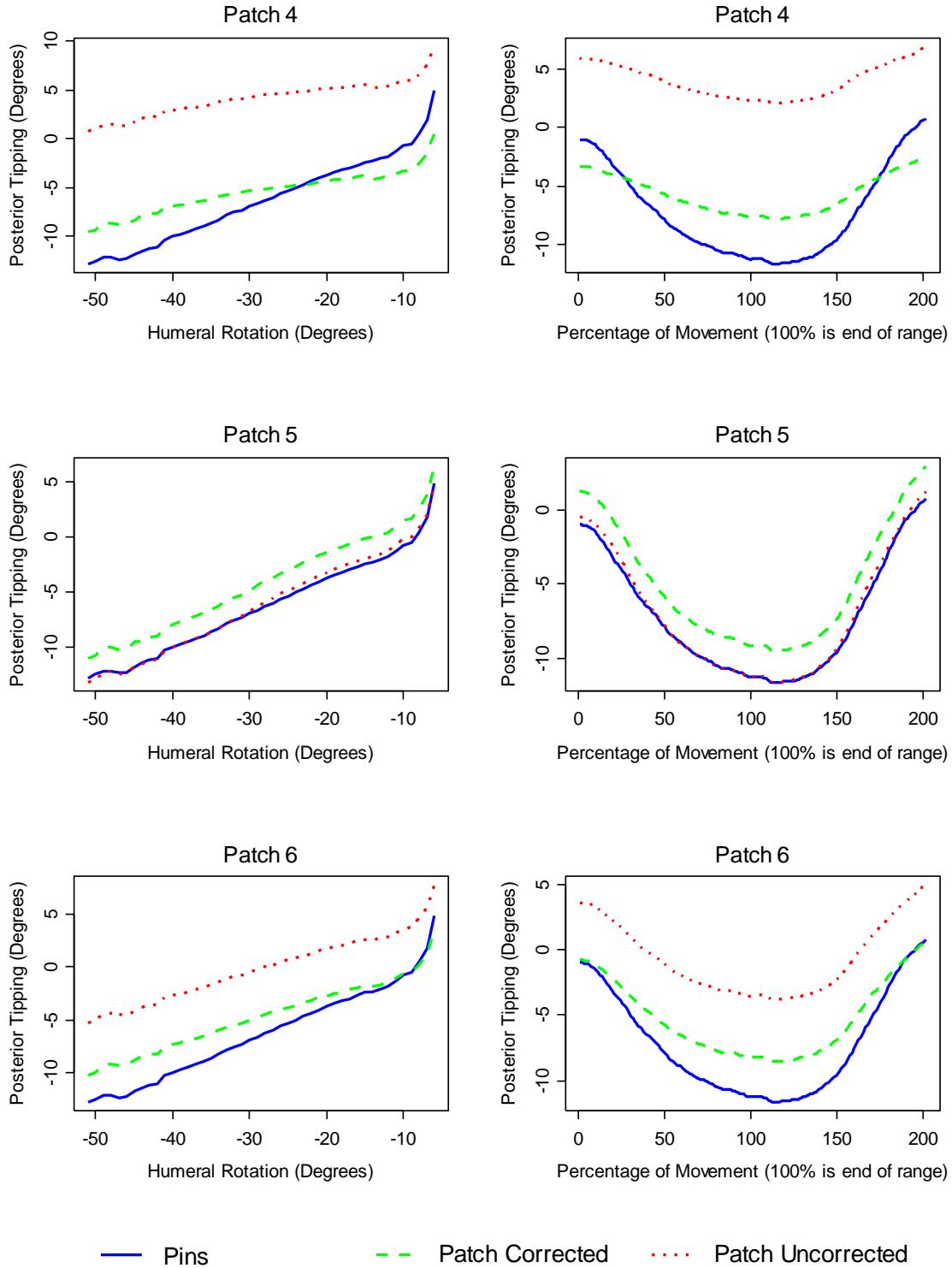
# Hand Behind Back: Pins vs. Patches Subject1

## Posterior Tipping

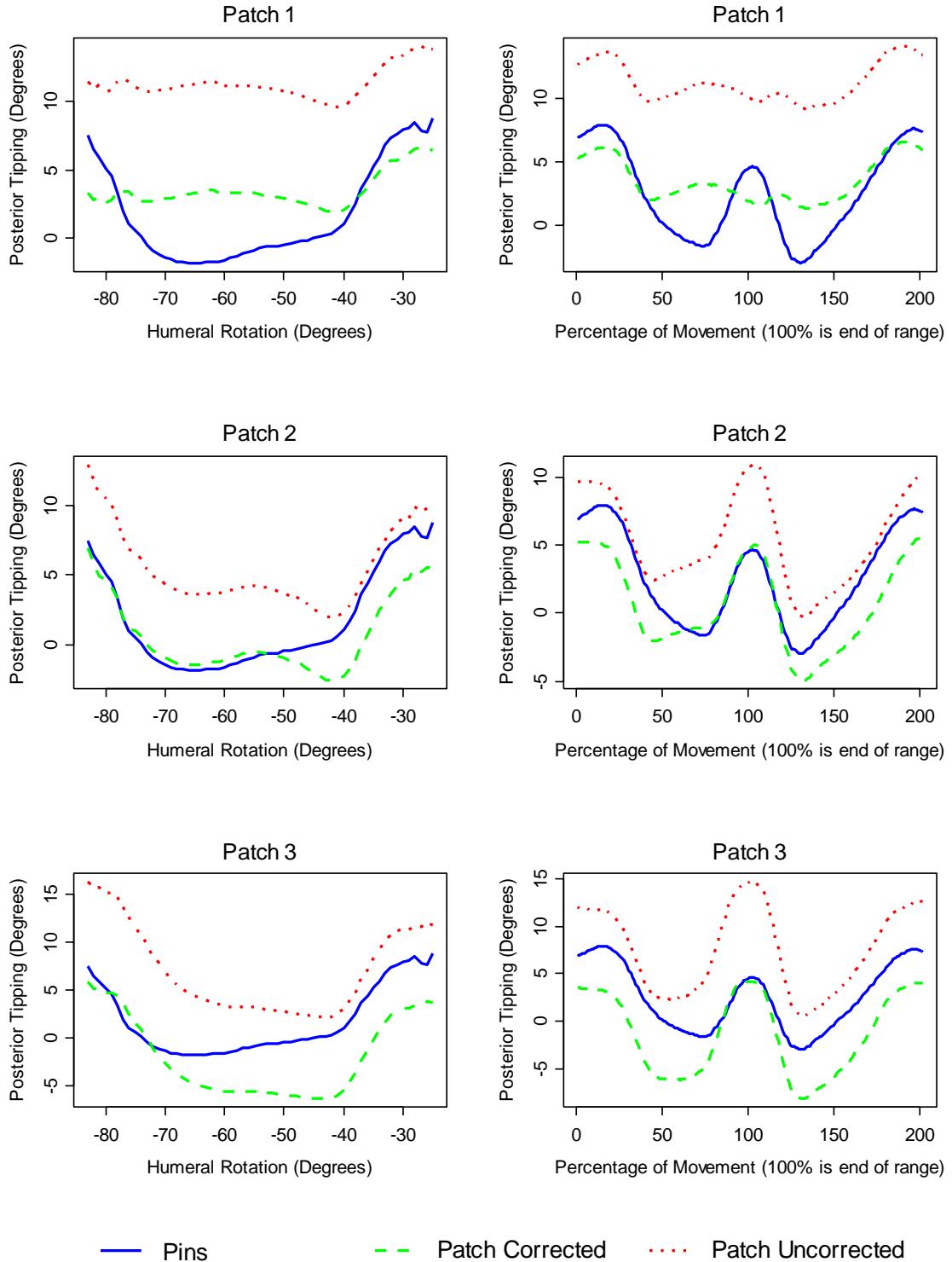


# Hand Behind Back: Pins vs. Patches Subject1

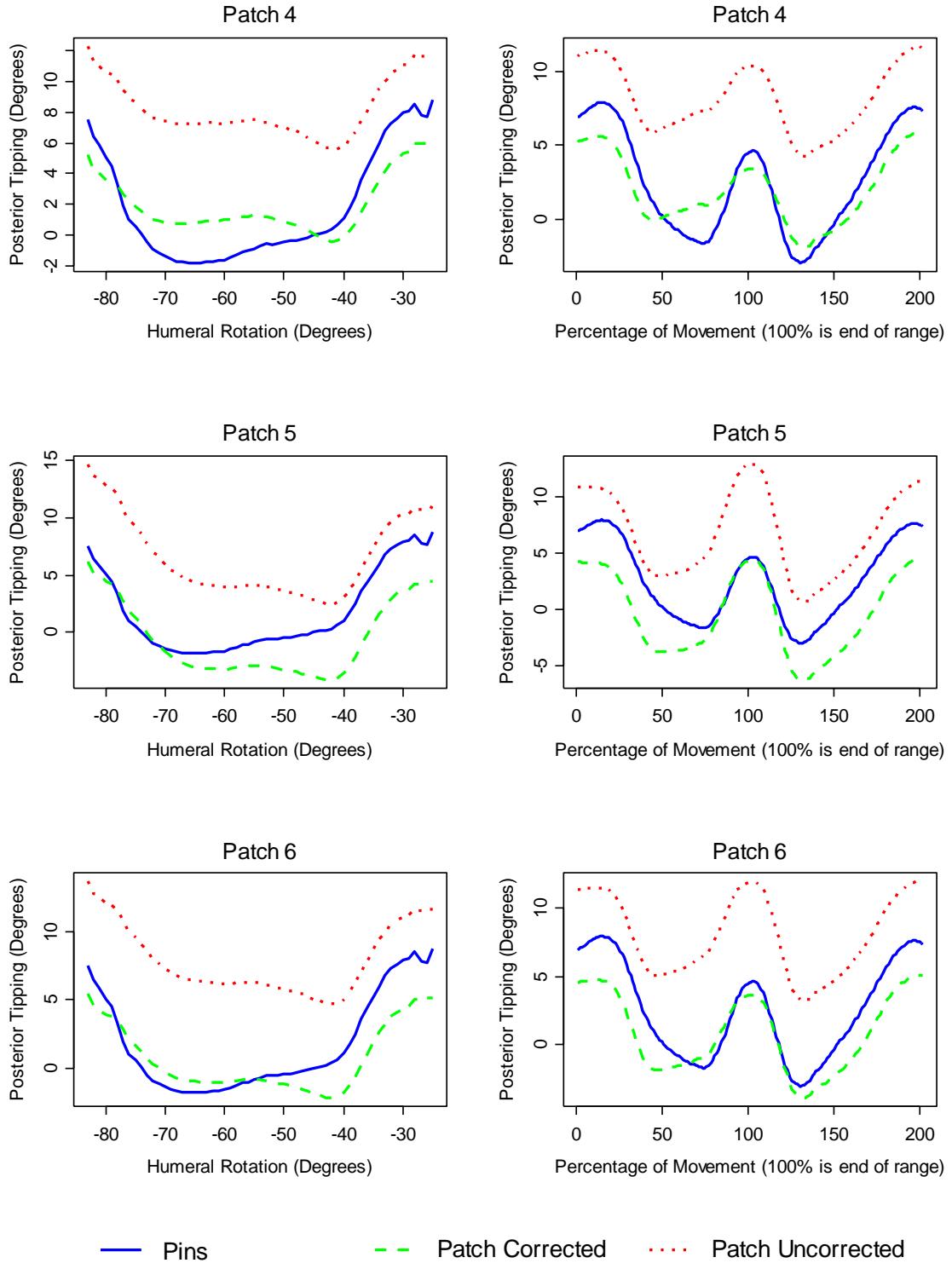
## Posterior Tipping



## Hand Behind Back: Pins vs. Patches Subject2 Posterior Tipping

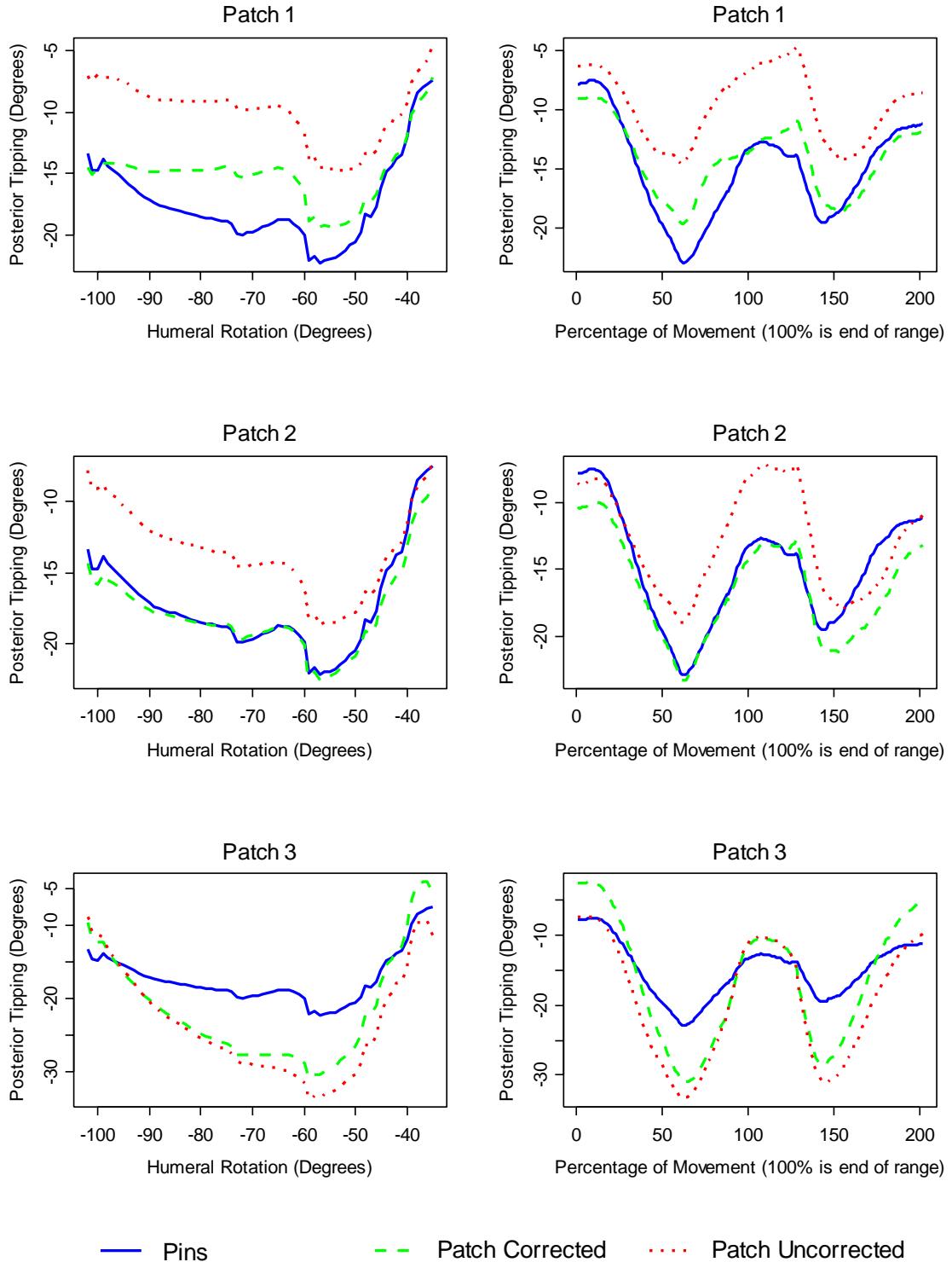


## Hand Behind Back: Pins vs. Patches Subject2 Posterior Tipping



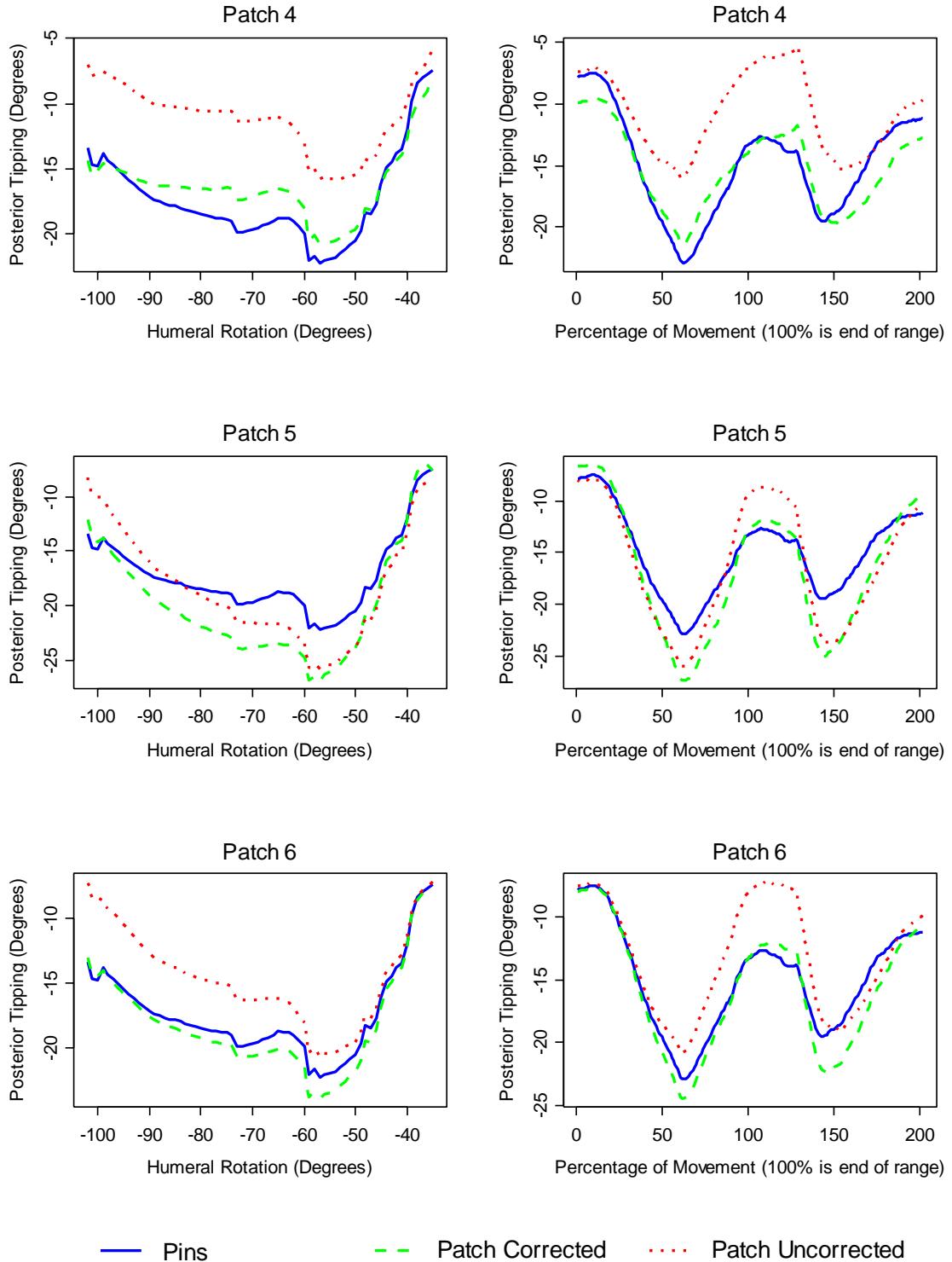
# Hand Behind Back: Pins vs. Patches Subject3

## Posterior Tipping

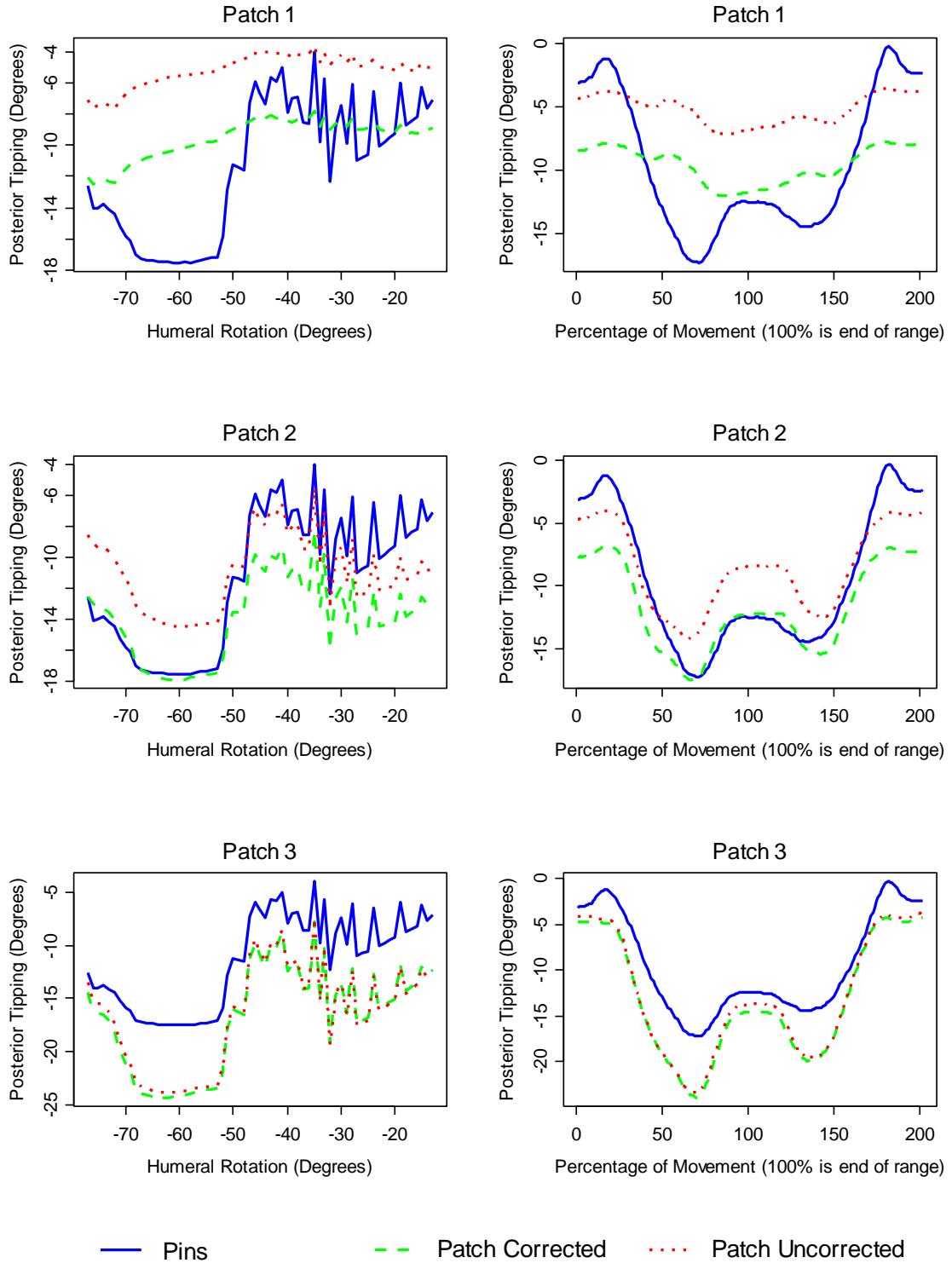


# Hand Behind Back: Pins vs. Patches Subject3

## Posterior Tipping

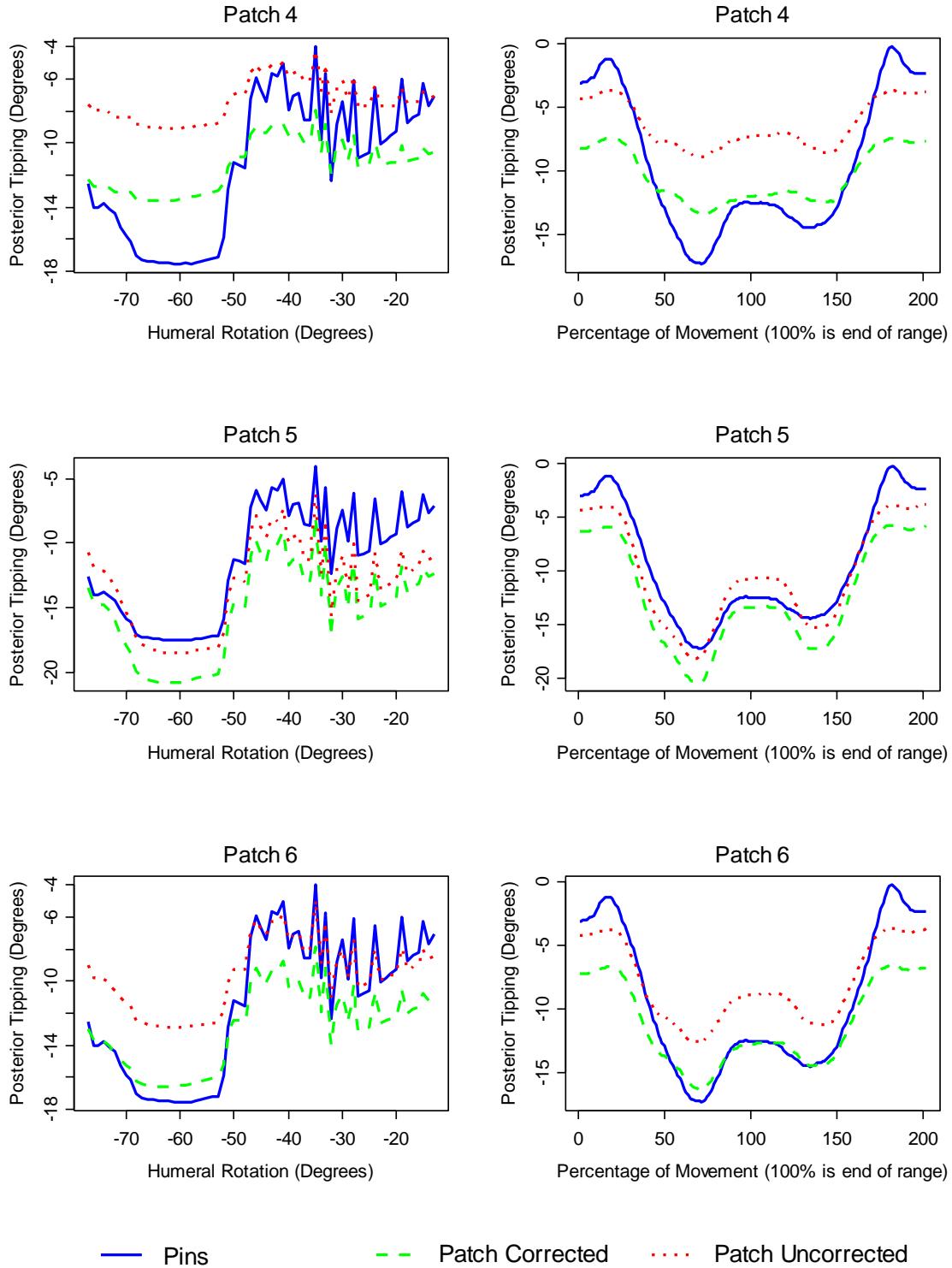


## Hand Behind Back: Pins vs. Patches Subject4 Posterior Tipping



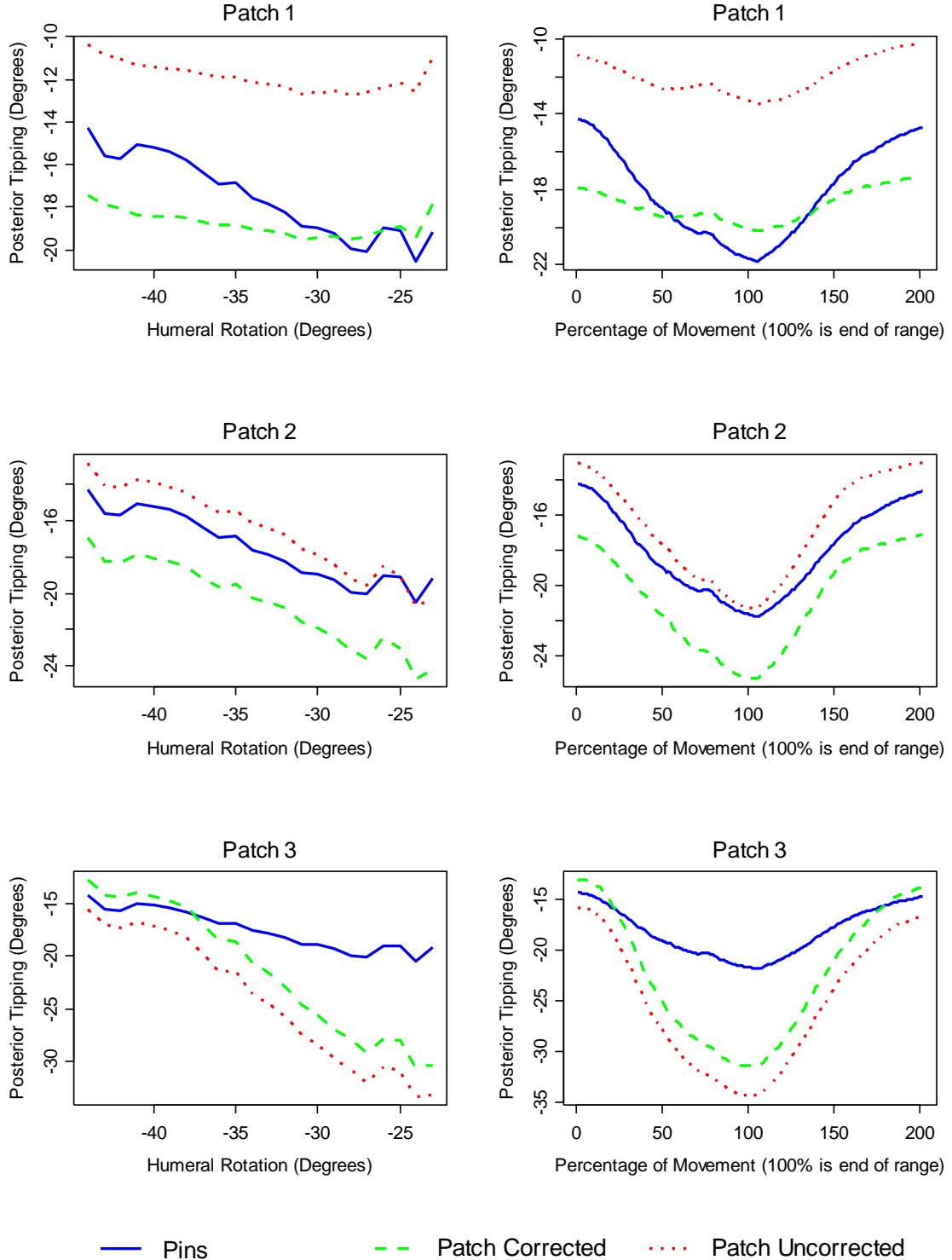
## Hand Behind Back: Pins vs. Patches Subject4

### Posterior Tipping



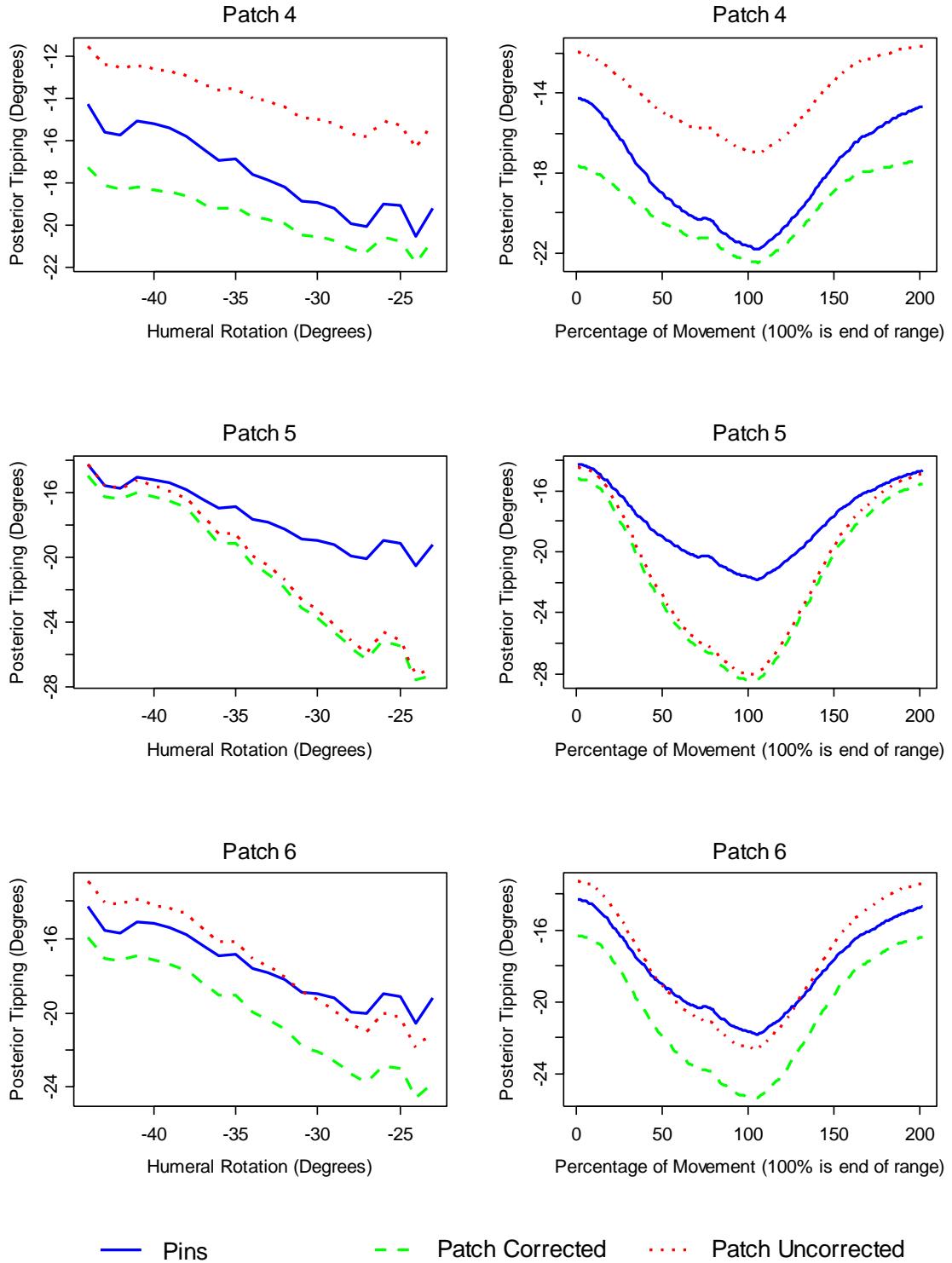
# Hand Behind Back: Pins vs. Patches Subject5

## Posterior Tipping



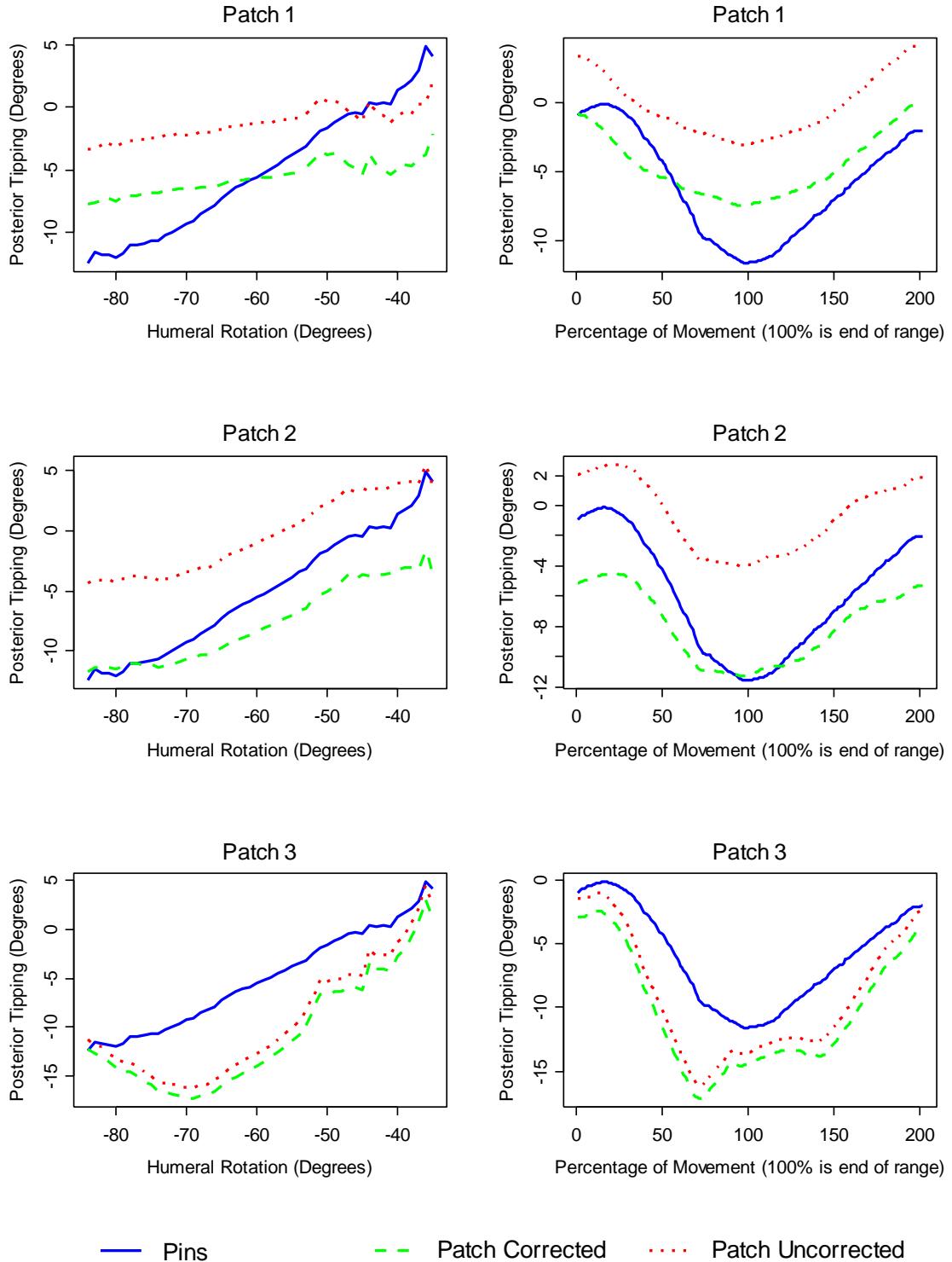
# Hand Behind Back: Pins vs. Patches Subject5

## Posterior Tipping



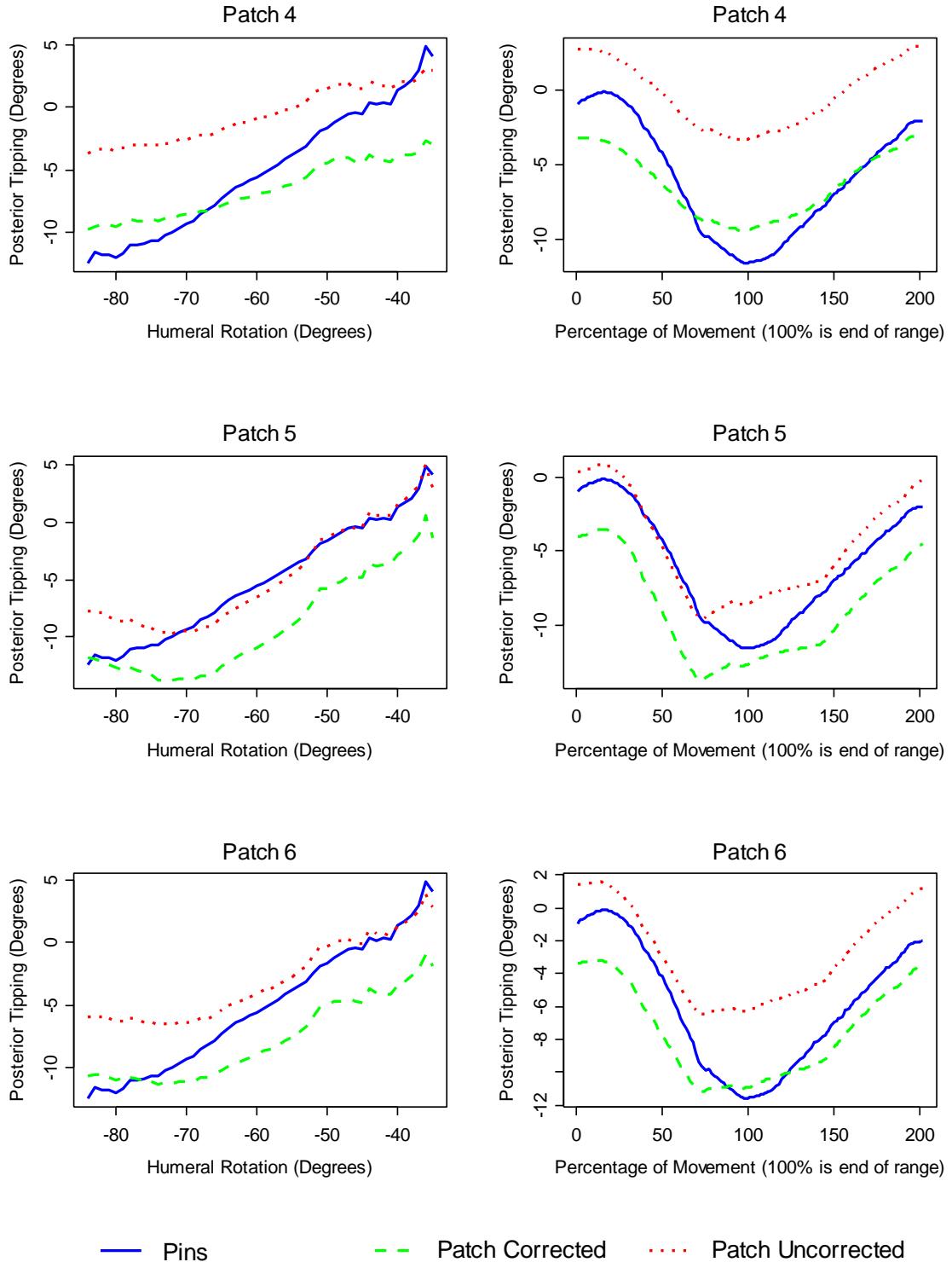
# Hand Behind Back: Pins vs. Patches Subject6

## Posterior Tipping



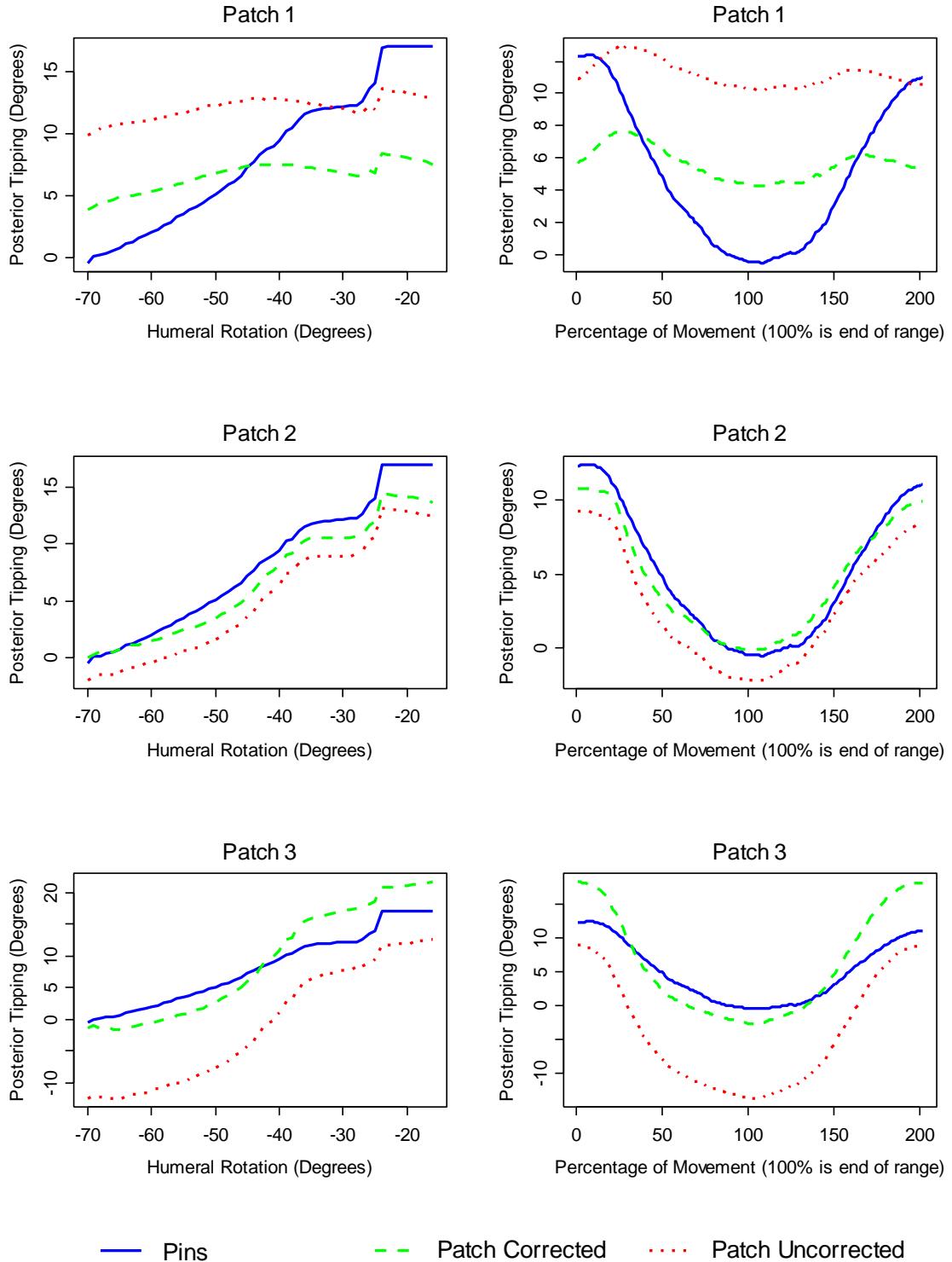
# Hand Behind Back: Pins vs. Patches Subject6

## Posterior Tipping



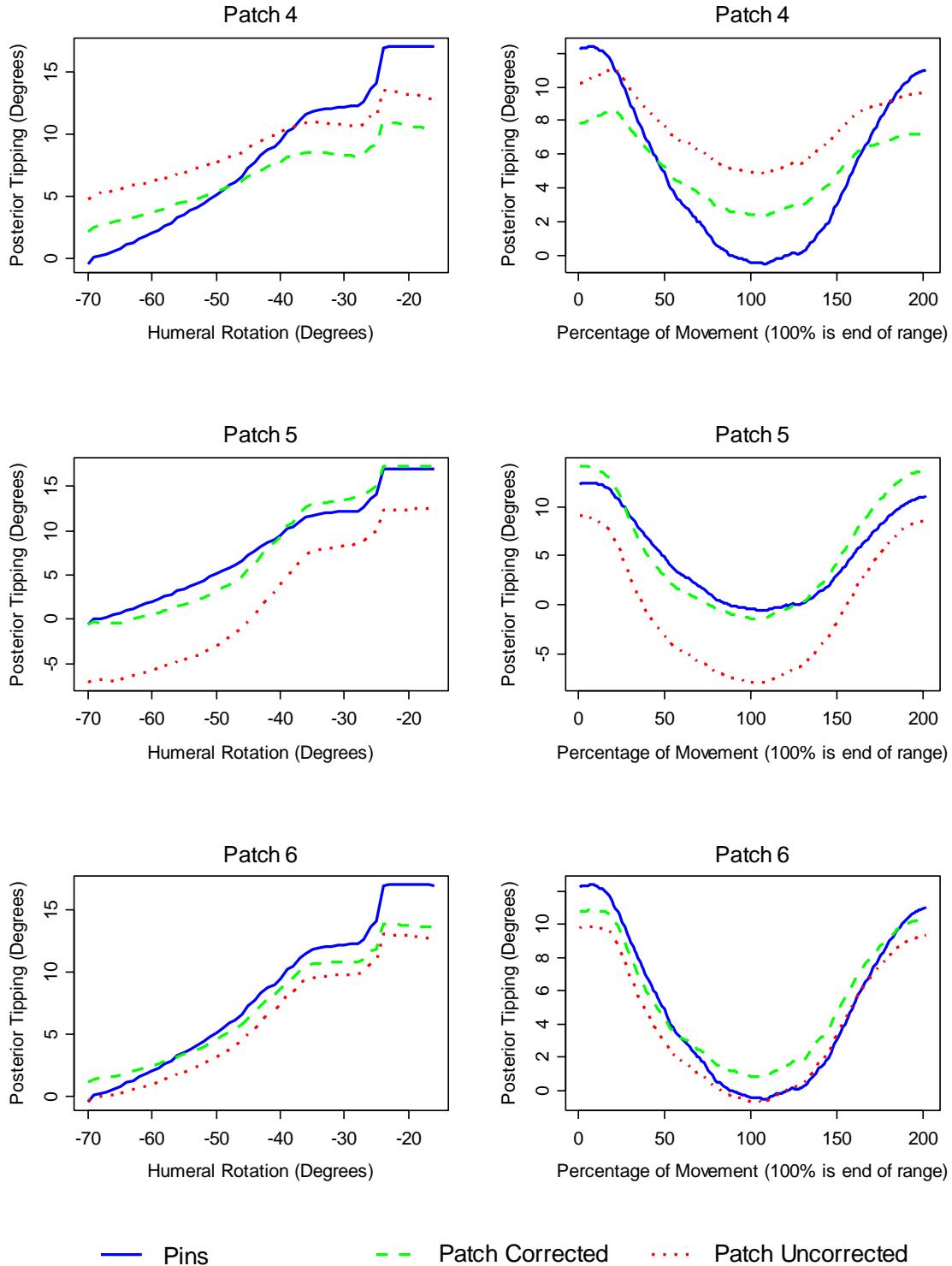
# Hand Behind Back: Pins vs. Patches Subject7

## Posterior Tipping



# Hand Behind Back: Pins vs. Patches Subject7

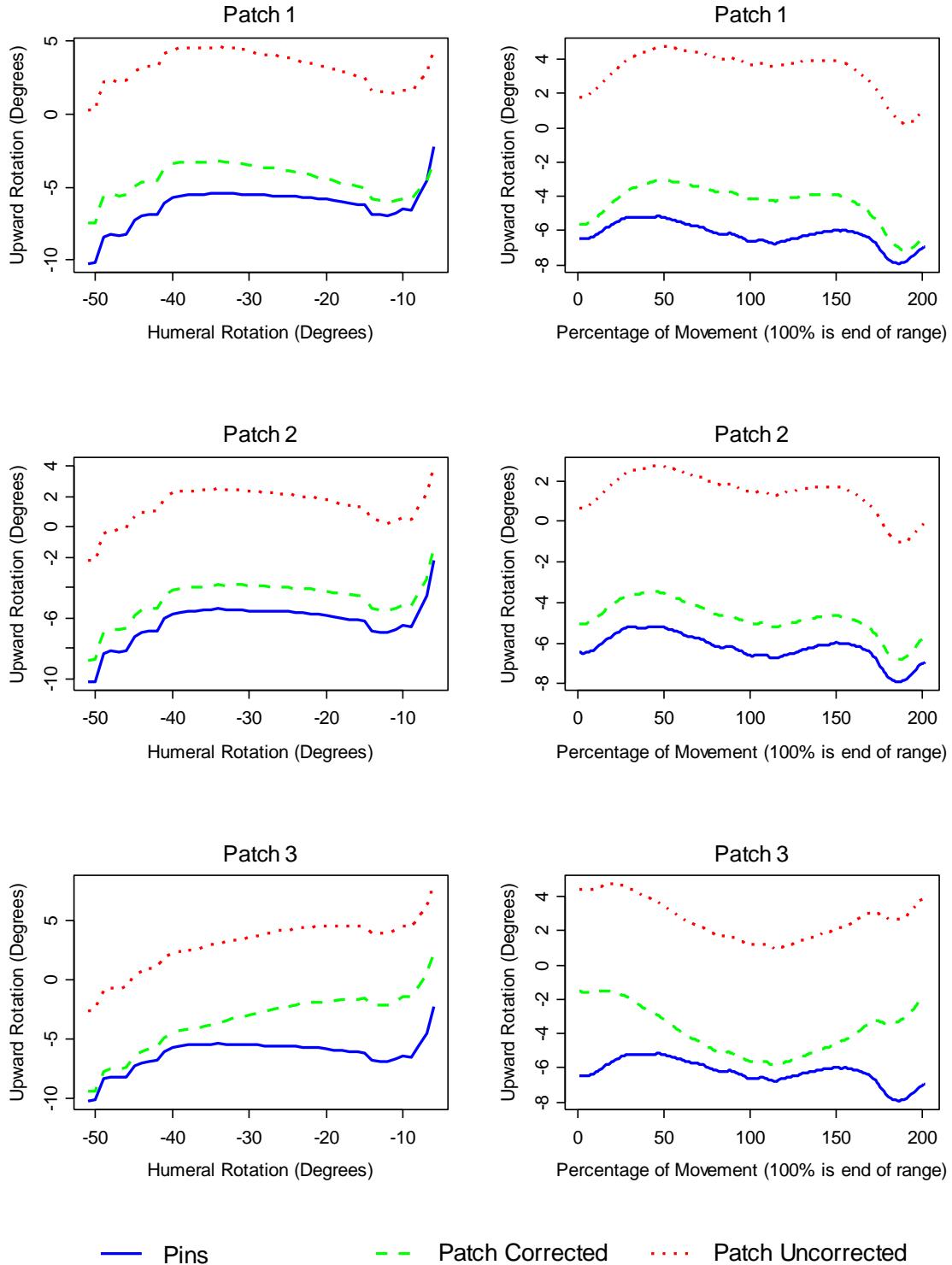
## Posterior Tipping



— Pins      - - - Patch Corrected      ... Patch Uncorrected

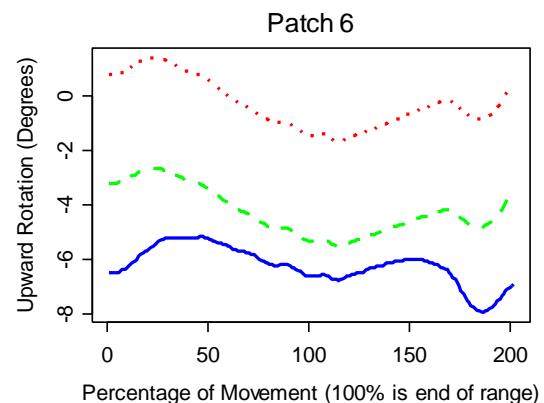
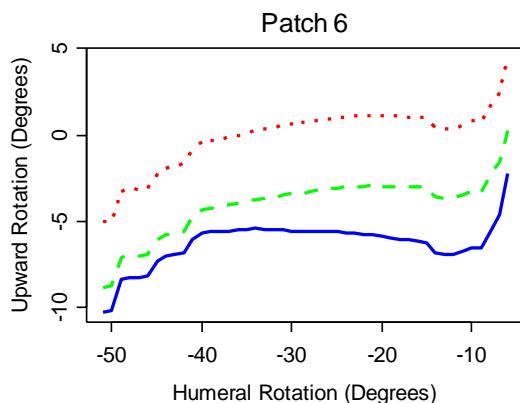
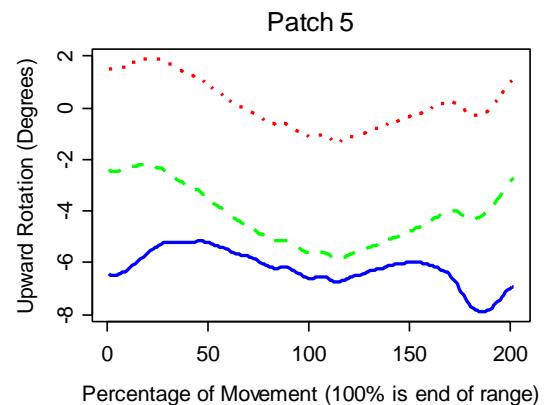
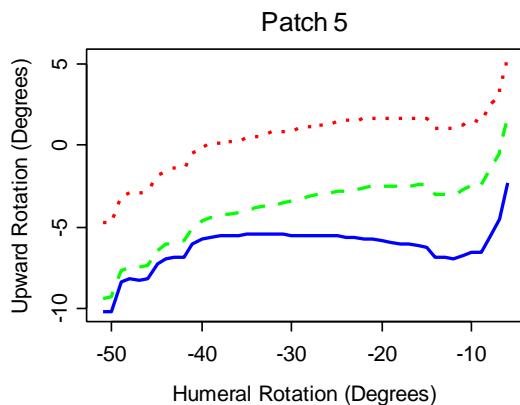
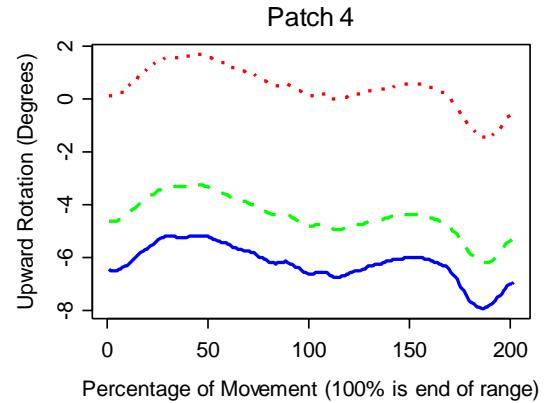
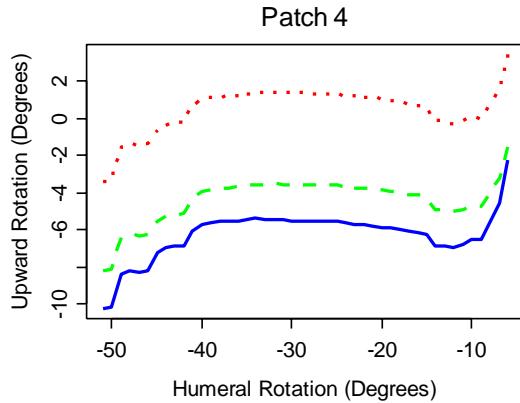
# Hand Behind Back: Pins vs. Patches Subject1

## Upward Rotation



# Hand Behind Back: Pins vs. Patches Subject1

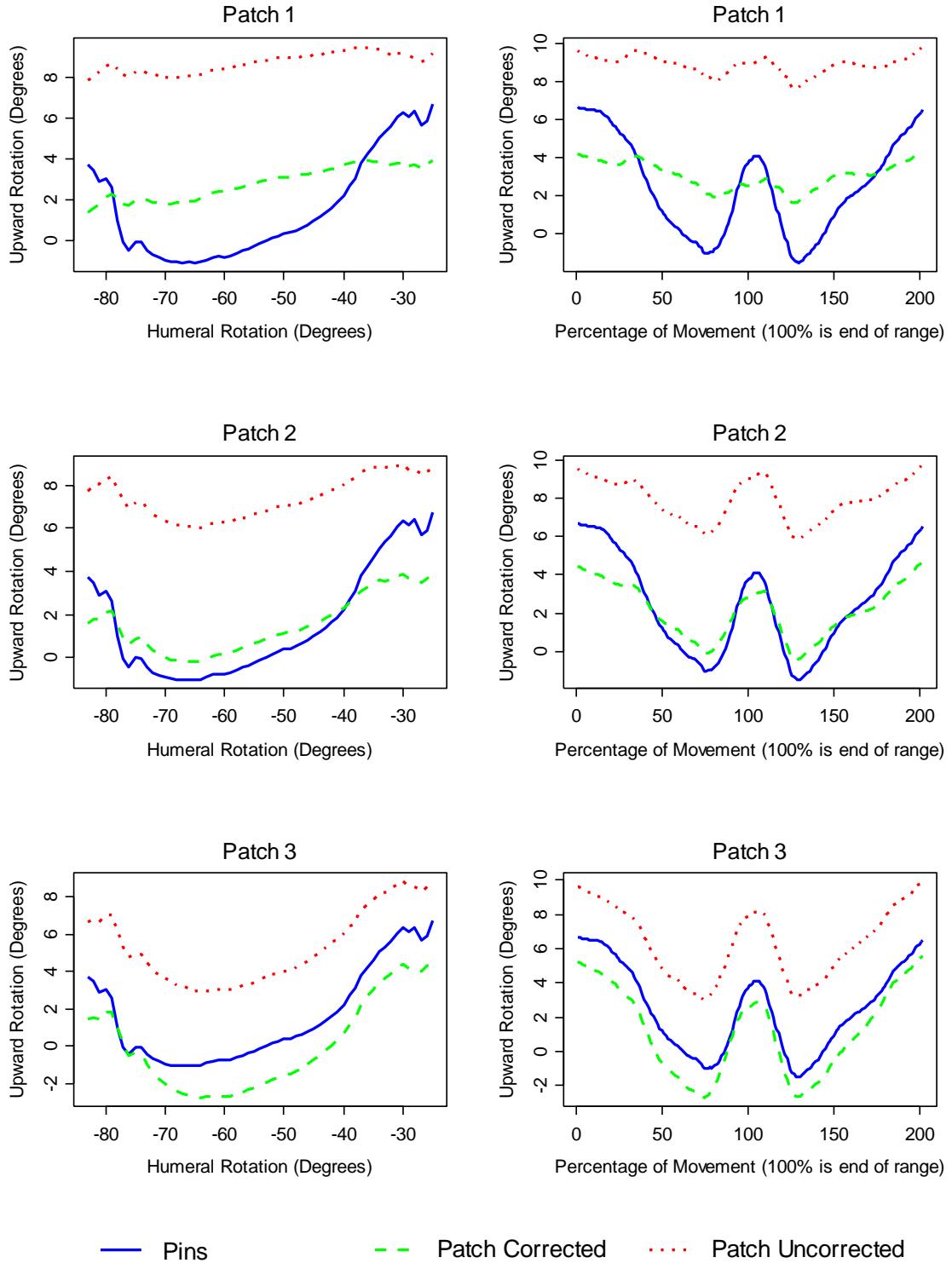
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

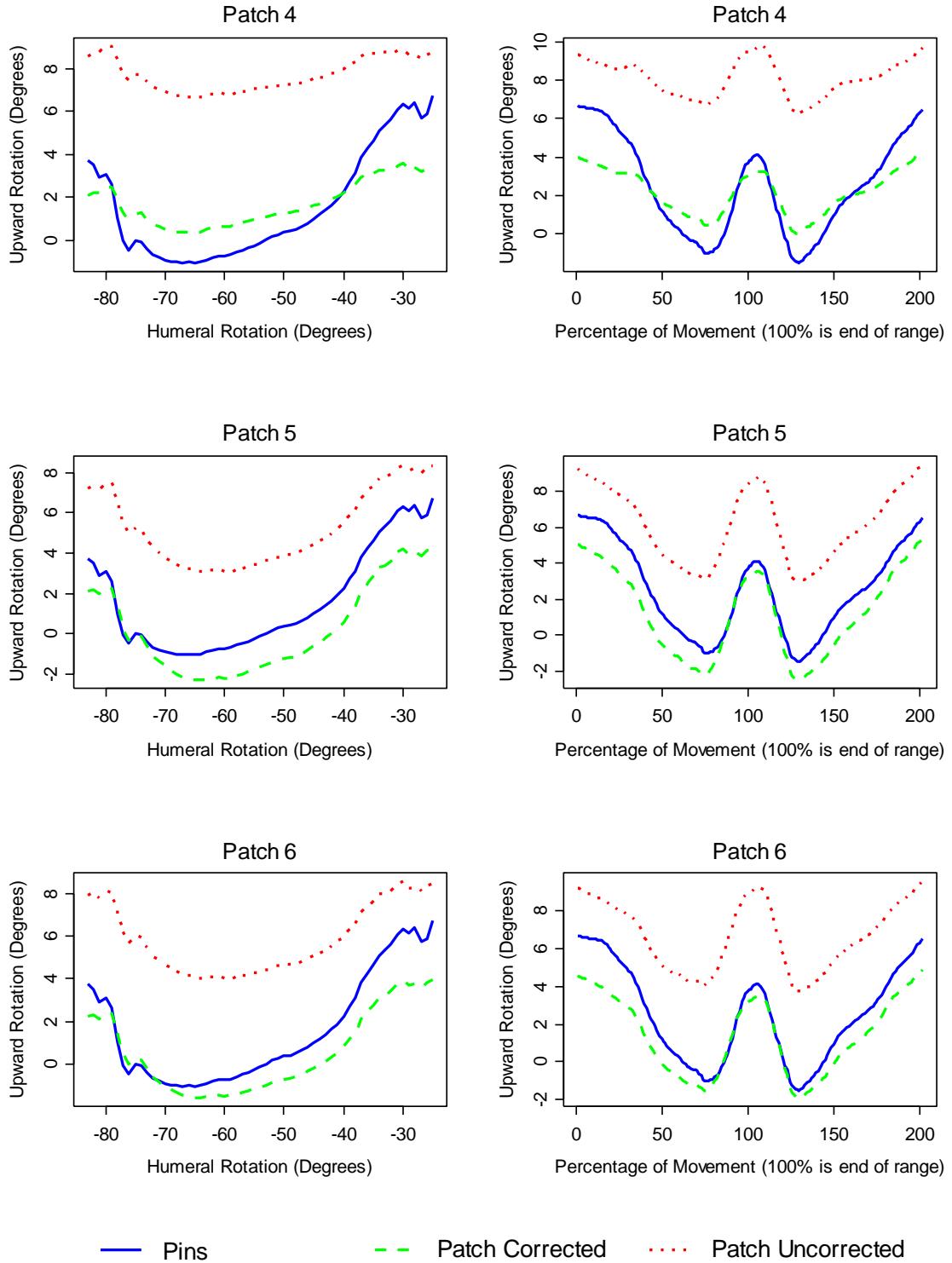
## Hand Behind Back: Pins vs. Patches Subject2

### Upward Rotation



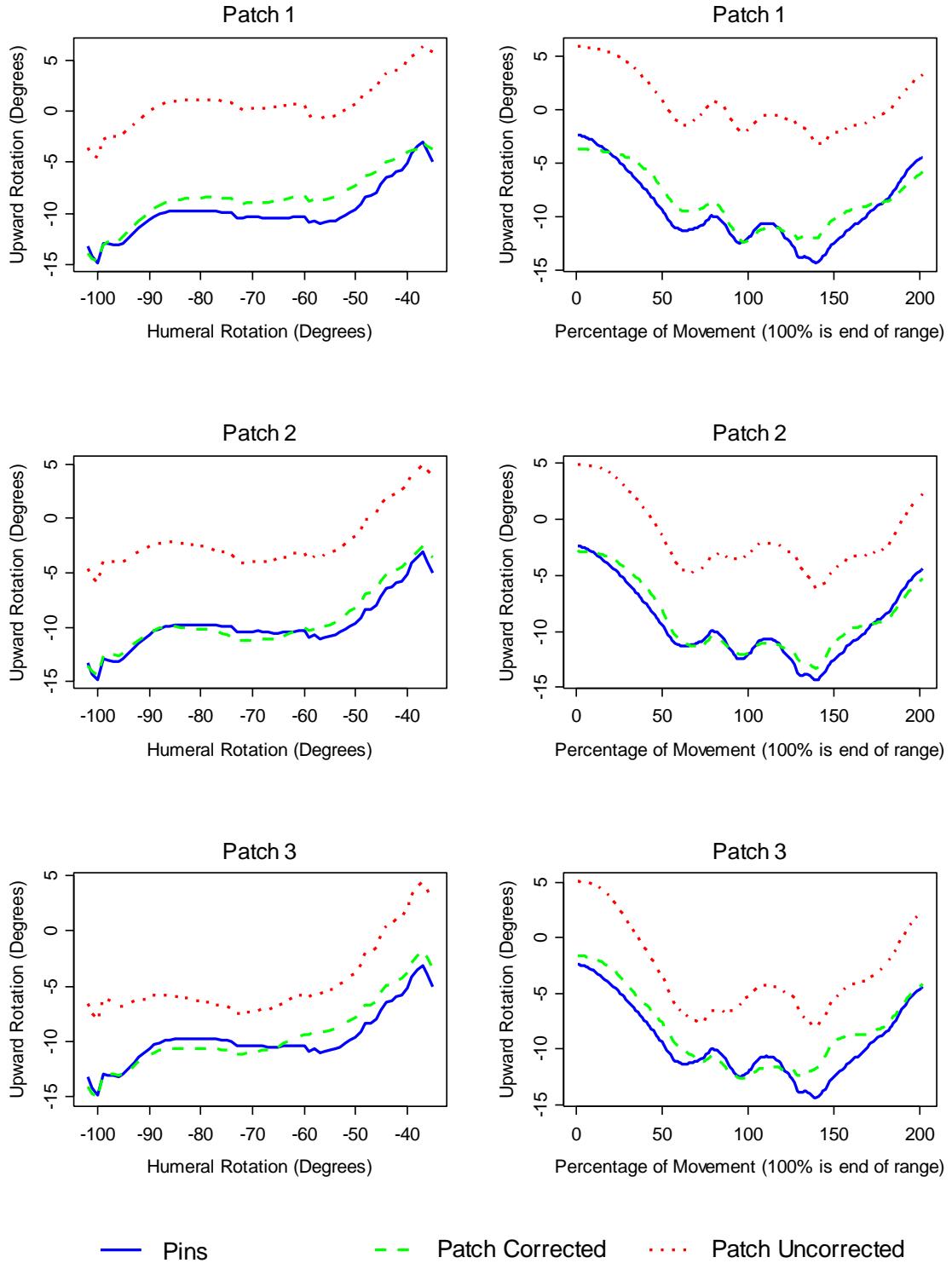
## Hand Behind Back: Pins vs. Patches Subject2

### Upward Rotation



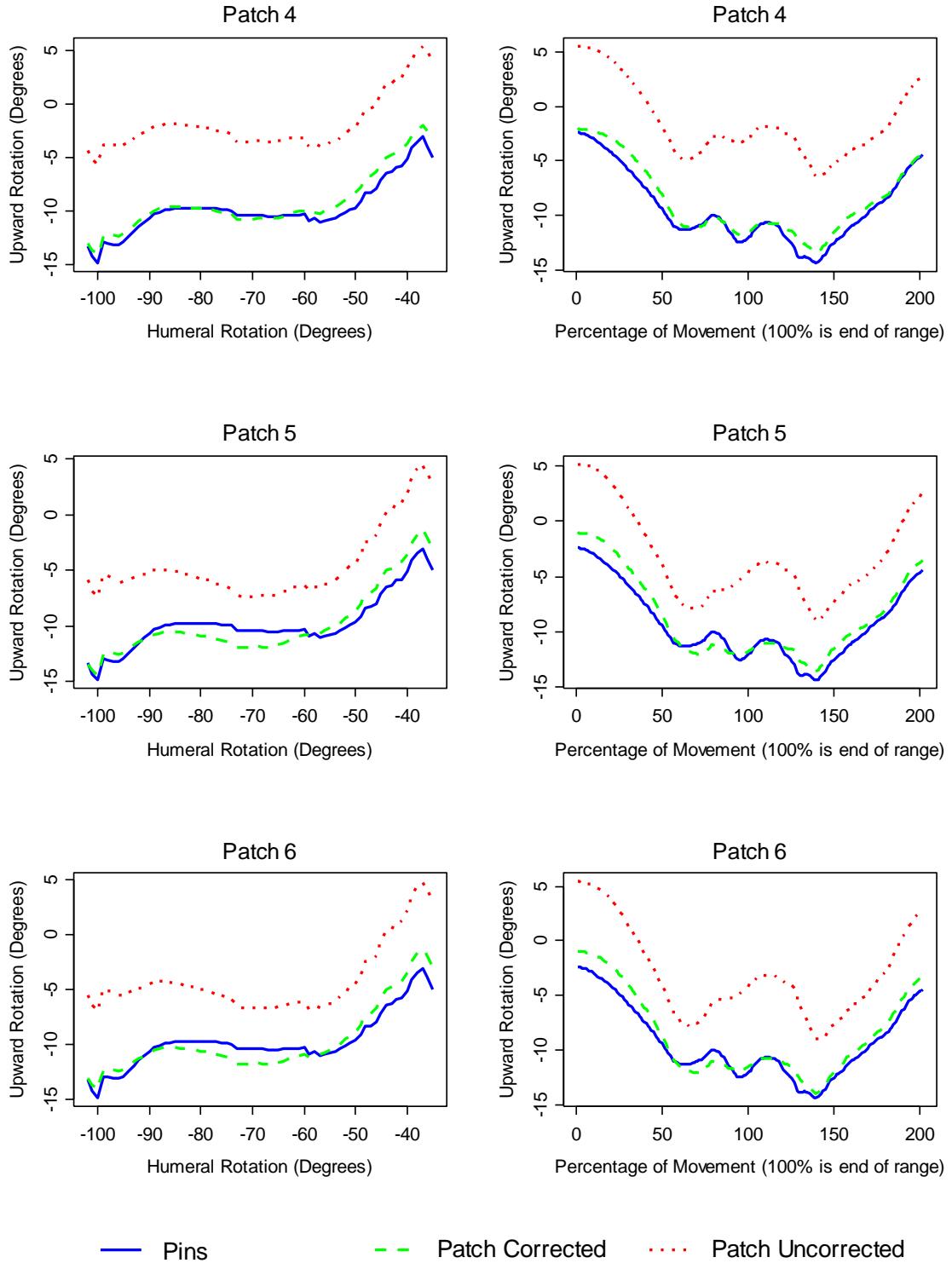
# Hand Behind Back: Pins vs. Patches Subject3

## Upward Rotation



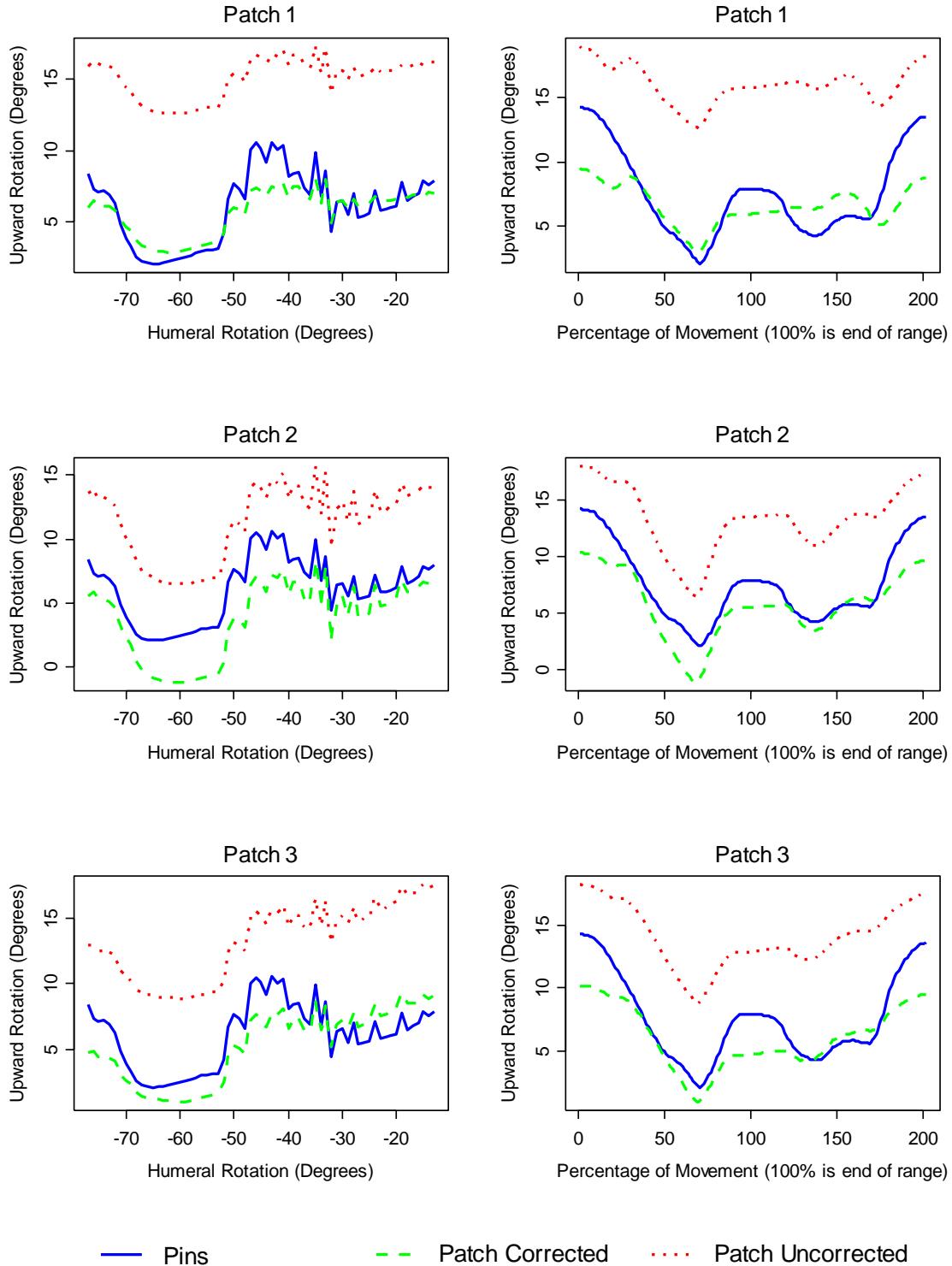
# Hand Behind Back: Pins vs. Patches Subject3

## Upward Rotation



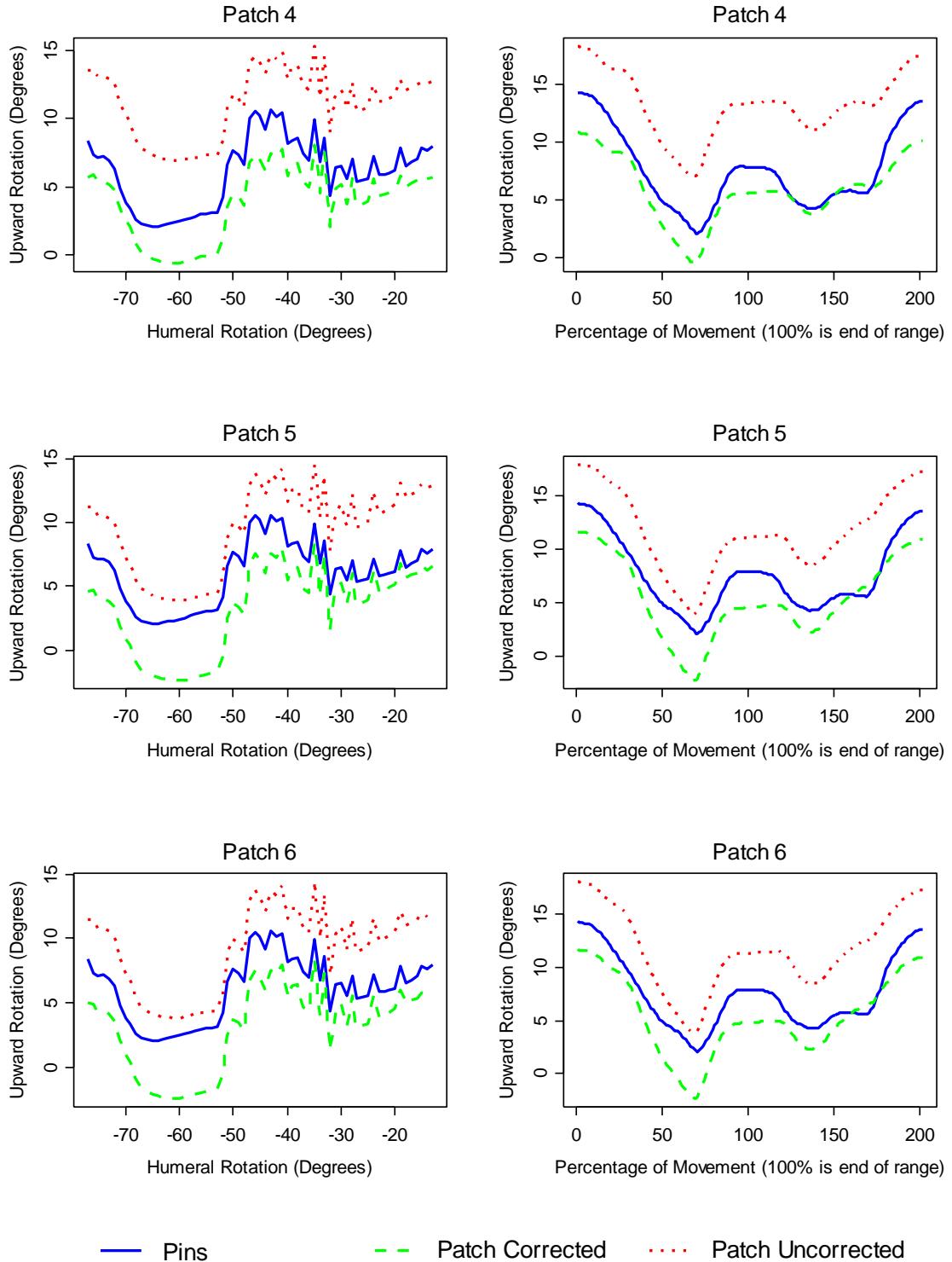
# Hand Behind Back: Pins vs. Patches Subject4

## Upward Rotation



## Hand Behind Back: Pins vs. Patches Subject4

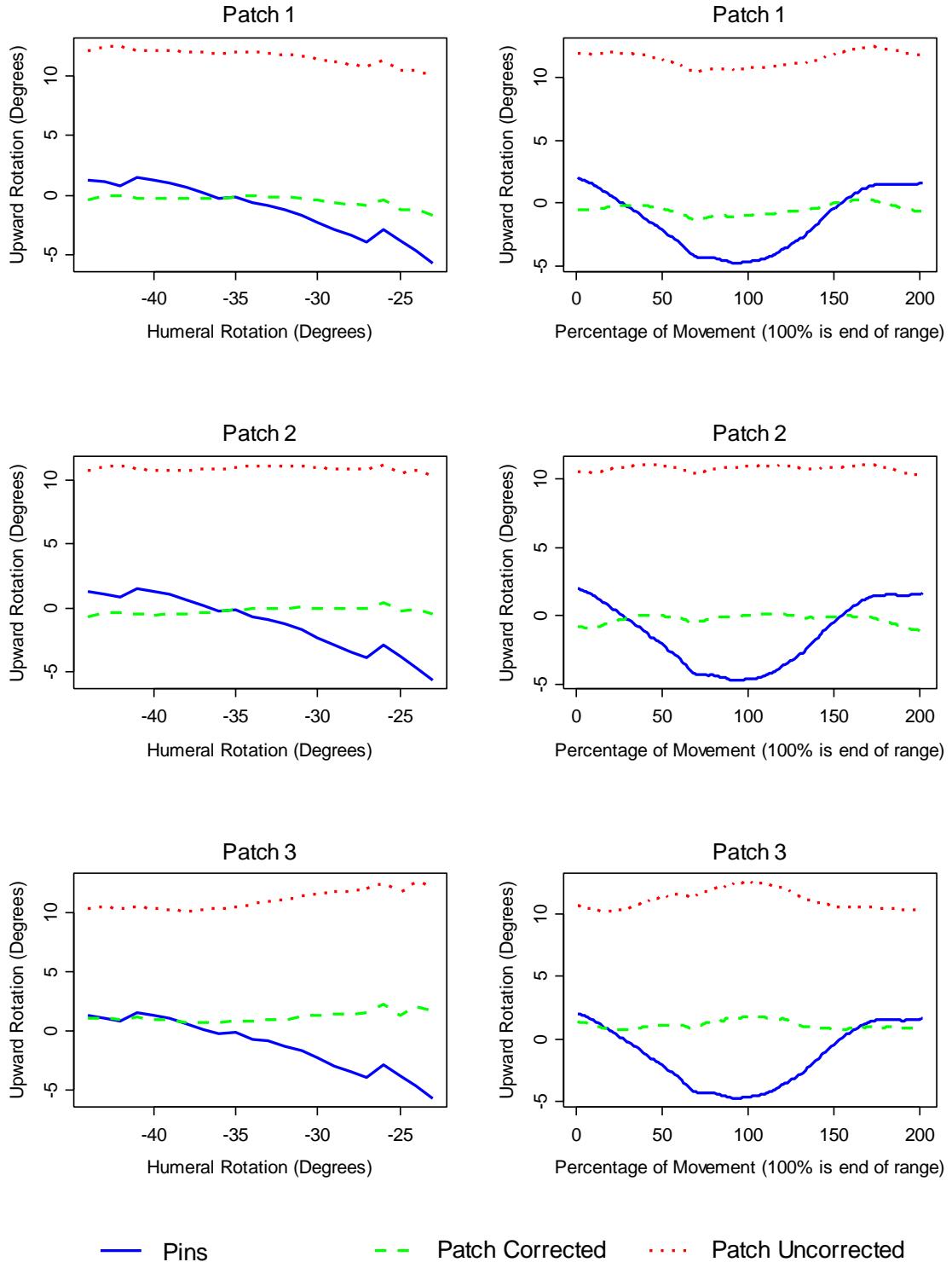
### Upward Rotation



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

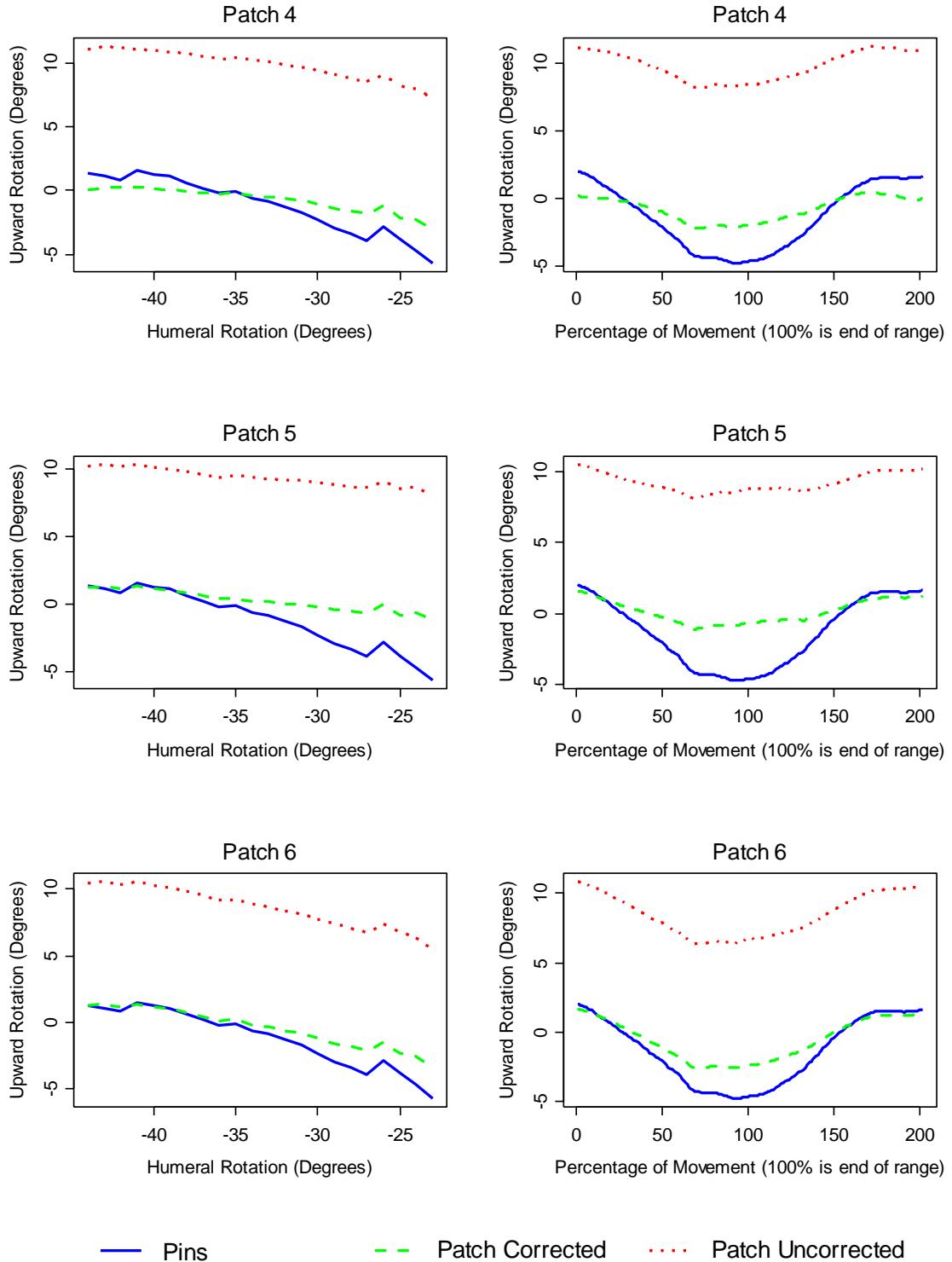
# Hand Behind Back: Pins vs. Patches Subject5

## Upward Rotation



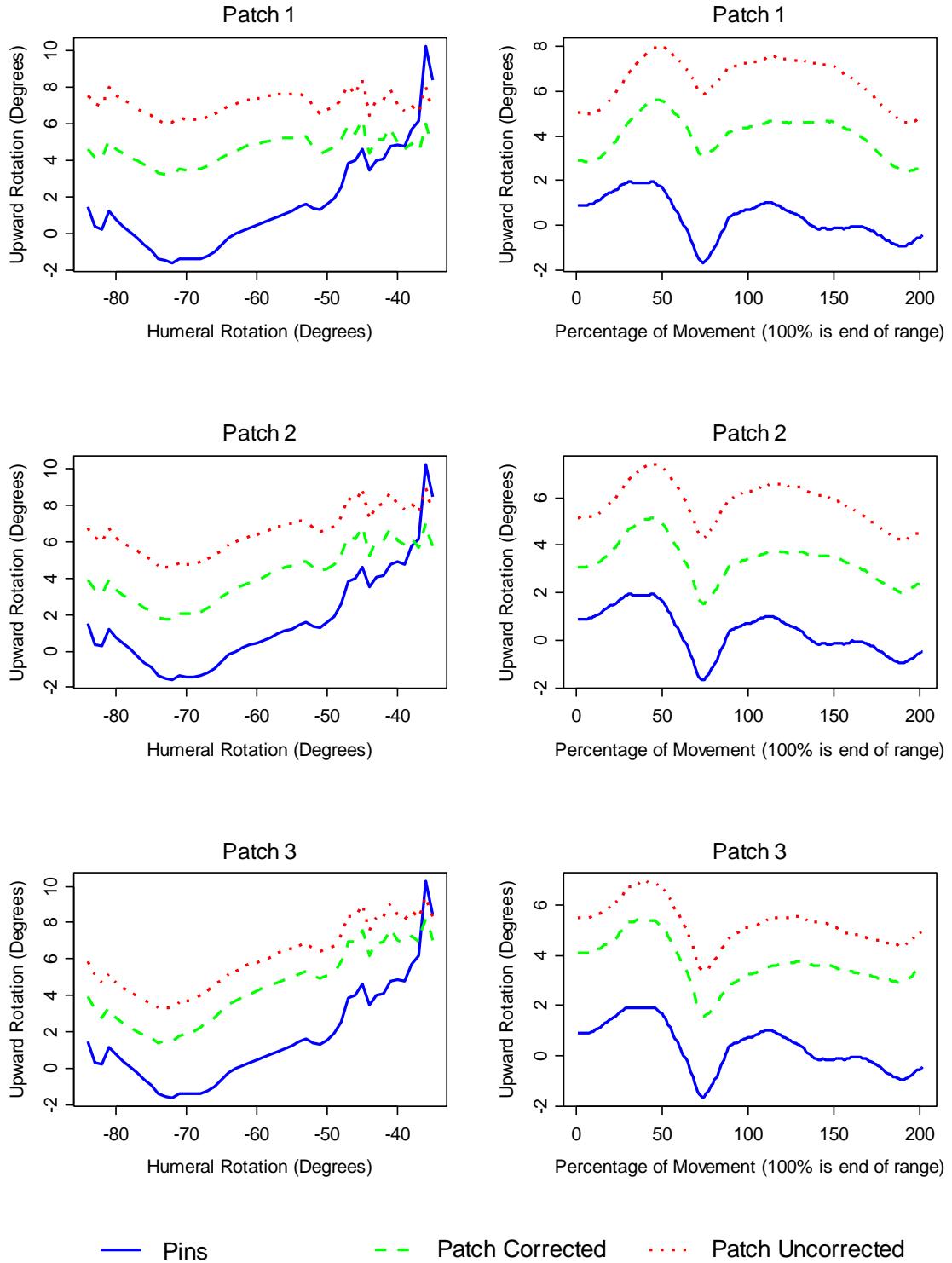
# Hand Behind Back: Pins vs. Patches Subject5

## Upward Rotation



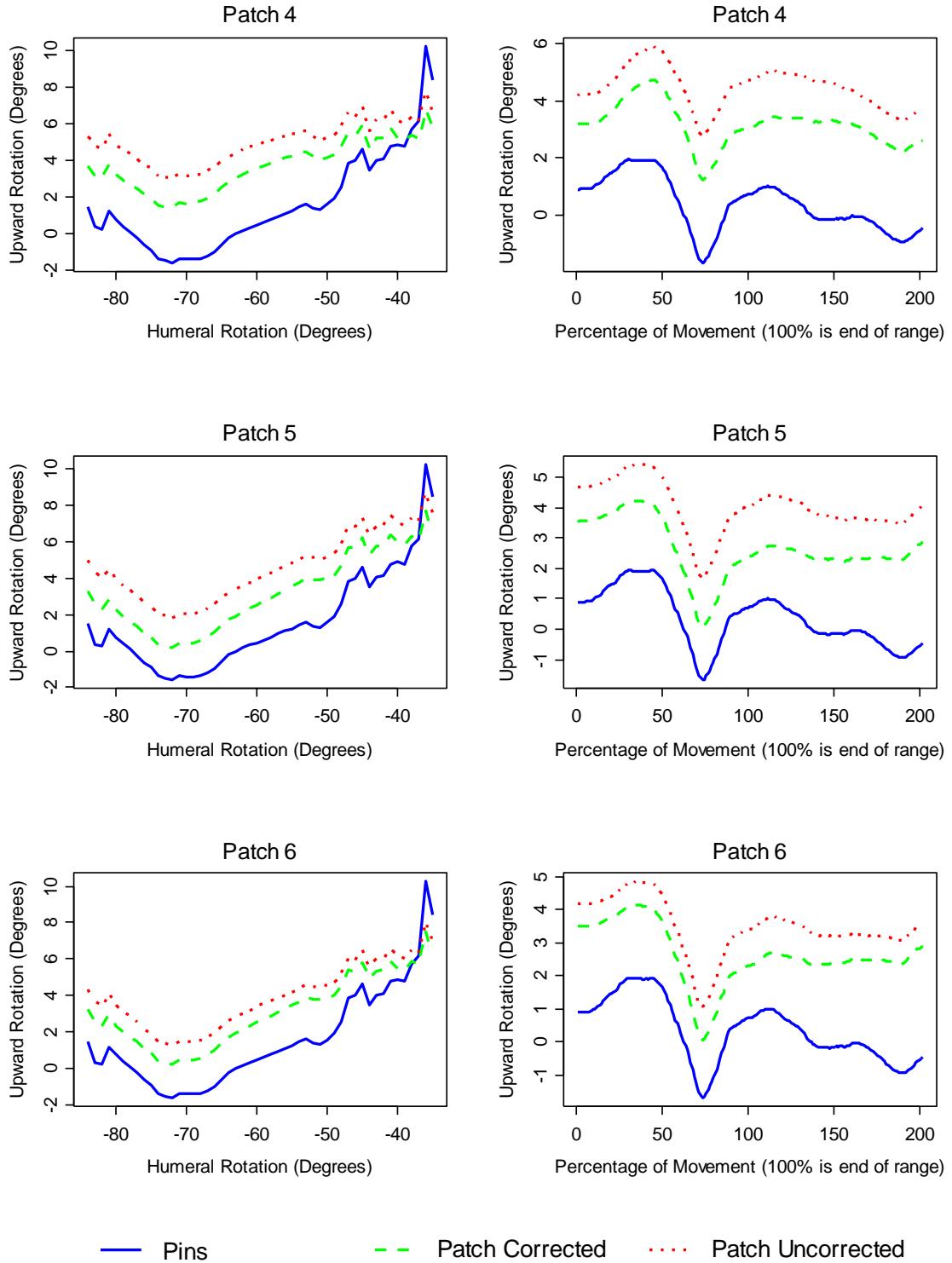
# Hand Behind Back: Pins vs. Patches Subject6

## Upward Rotation



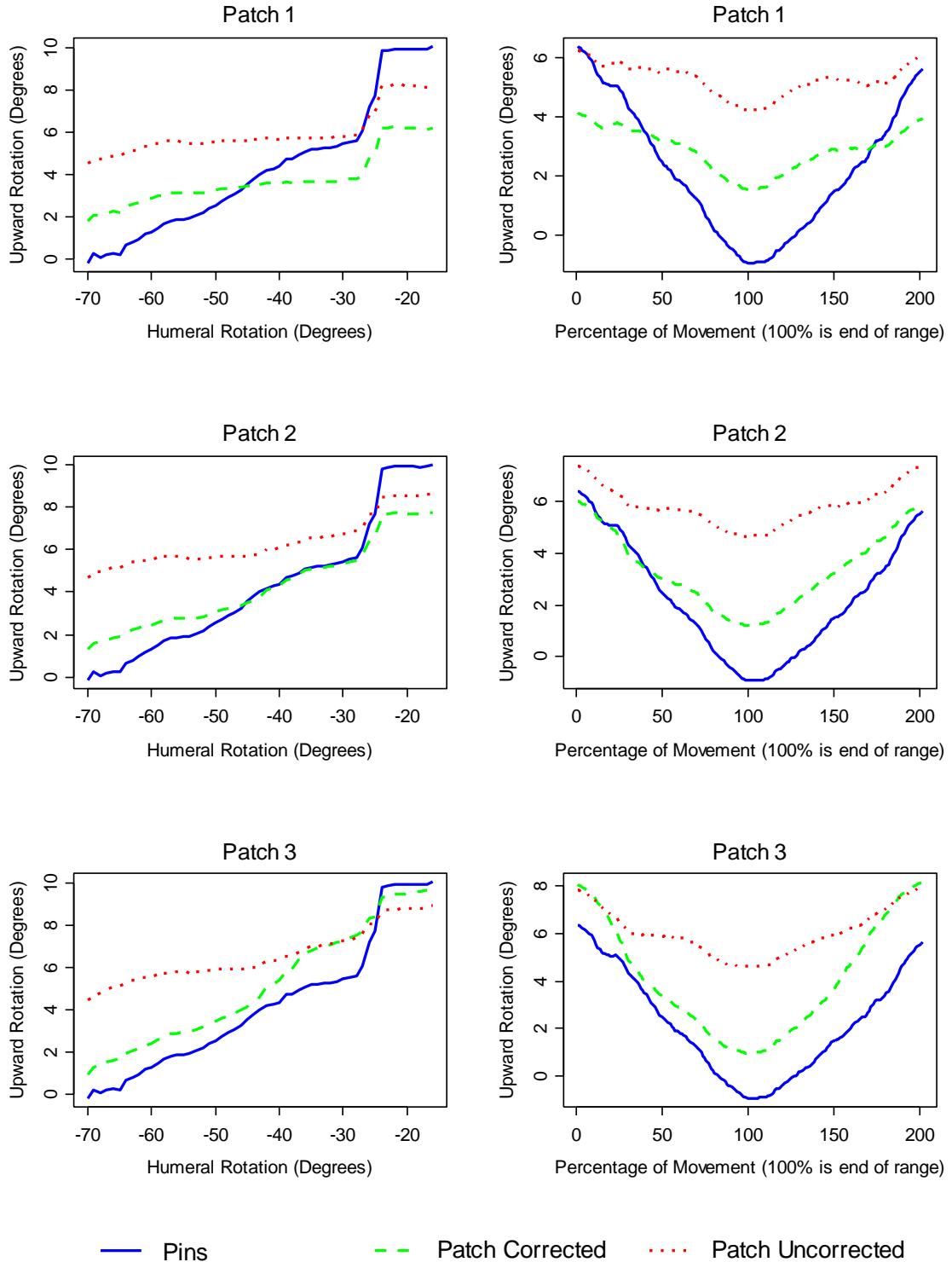
# Hand Behind Back: Pins vs. Patches Subject6

## Upward Rotation



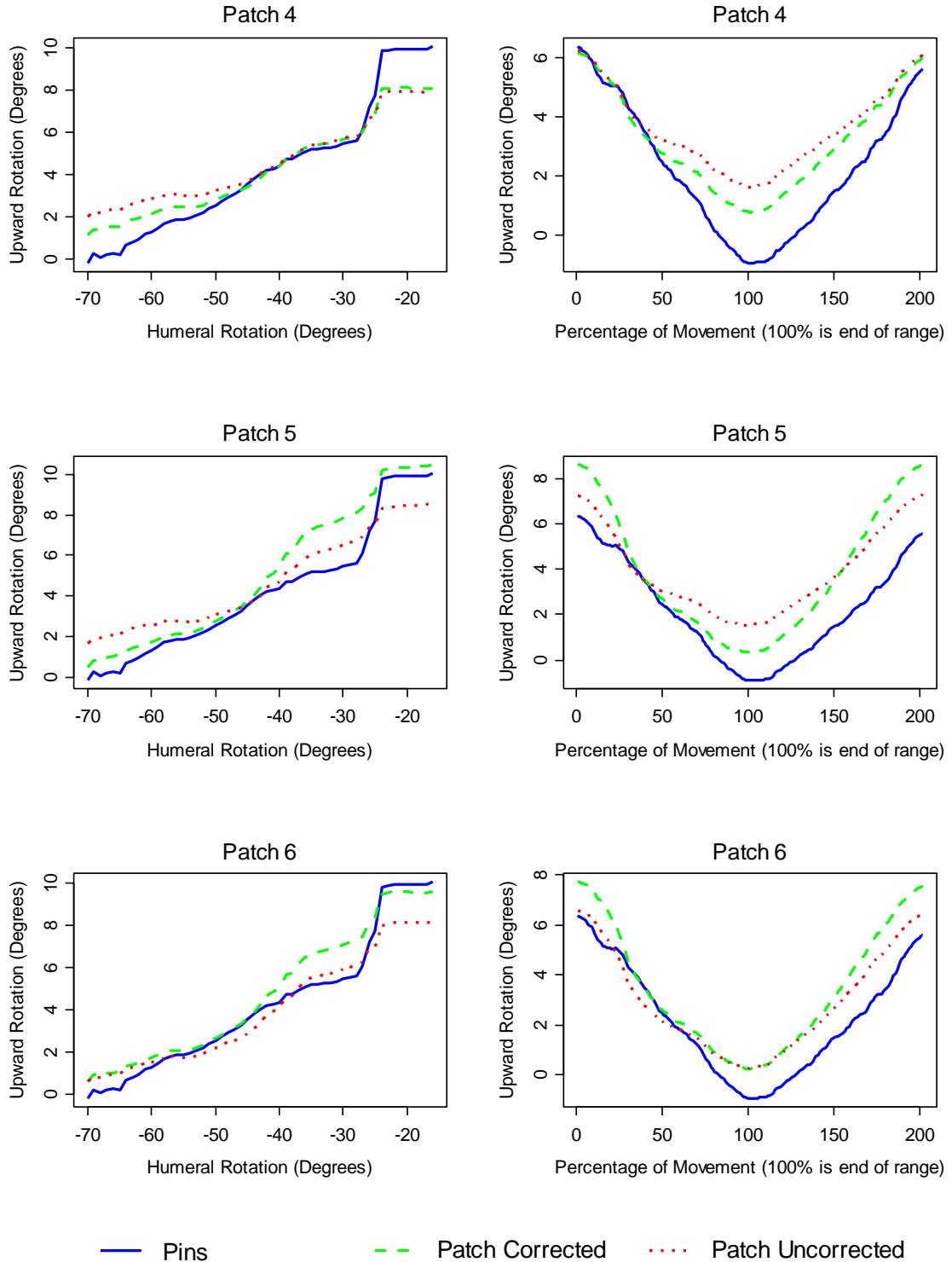
# Hand Behind Back: Pins vs. Patches Subject7

## Upward Rotation



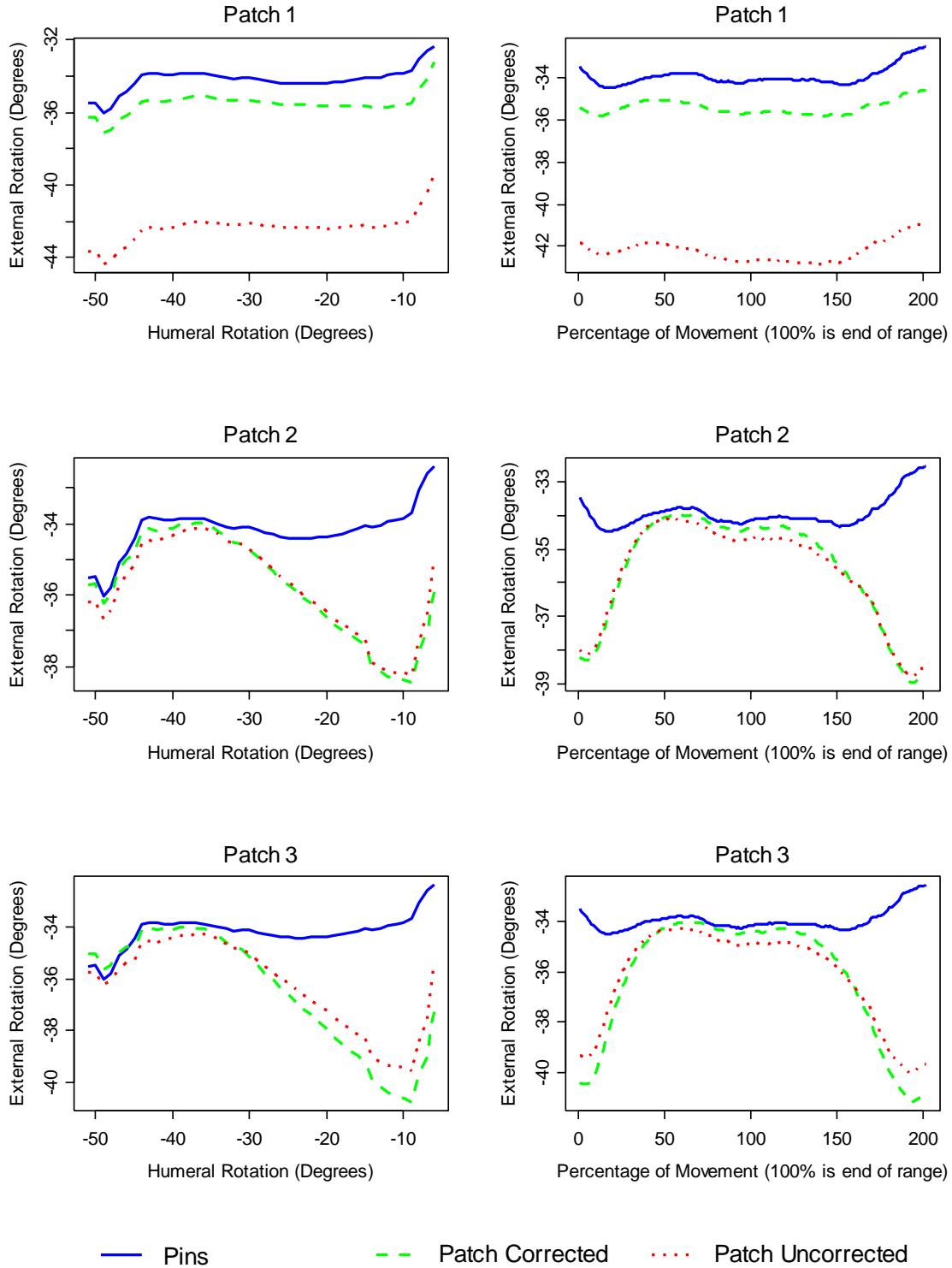
# Hand Behind Back: Pins vs. Patches Subject7

## Upward Rotation



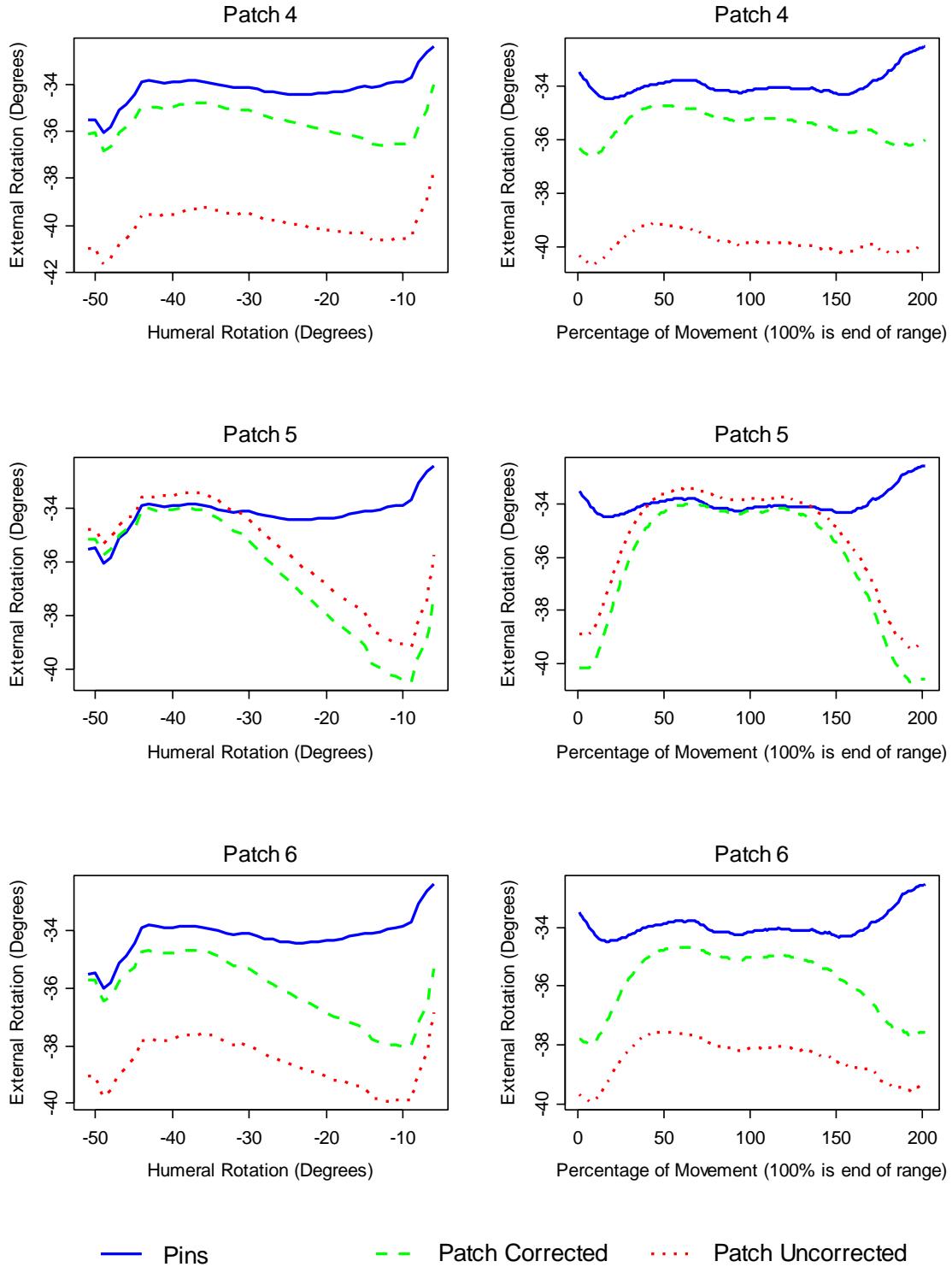
# Hand Behind Back: Pins vs. Patches Subject1

## External Rotation

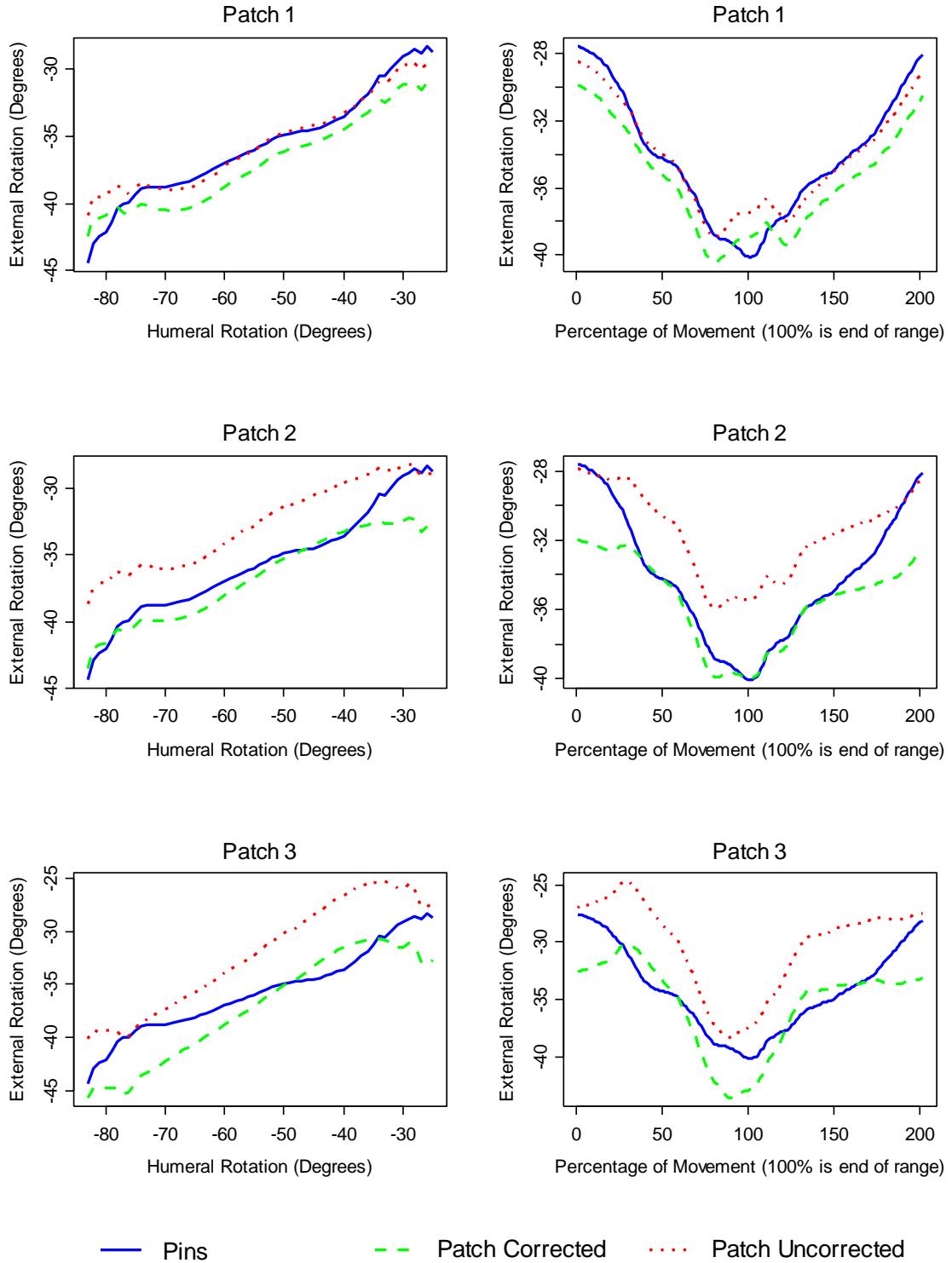


# Hand Behind Back: Pins vs. Patches Subject1

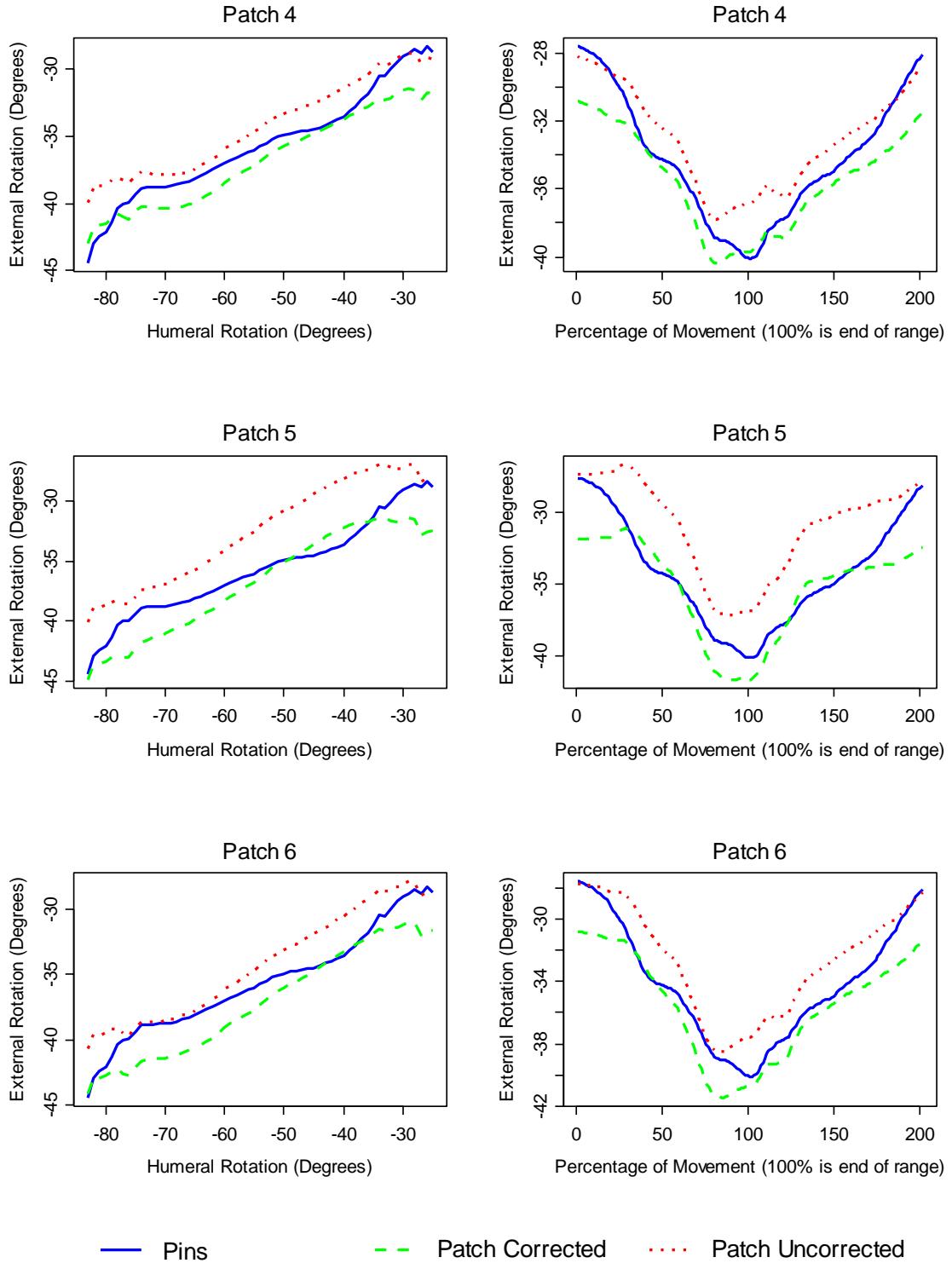
## External Rotation



## Hand Behind Back: Pins vs. Patches Subject2 External Rotation

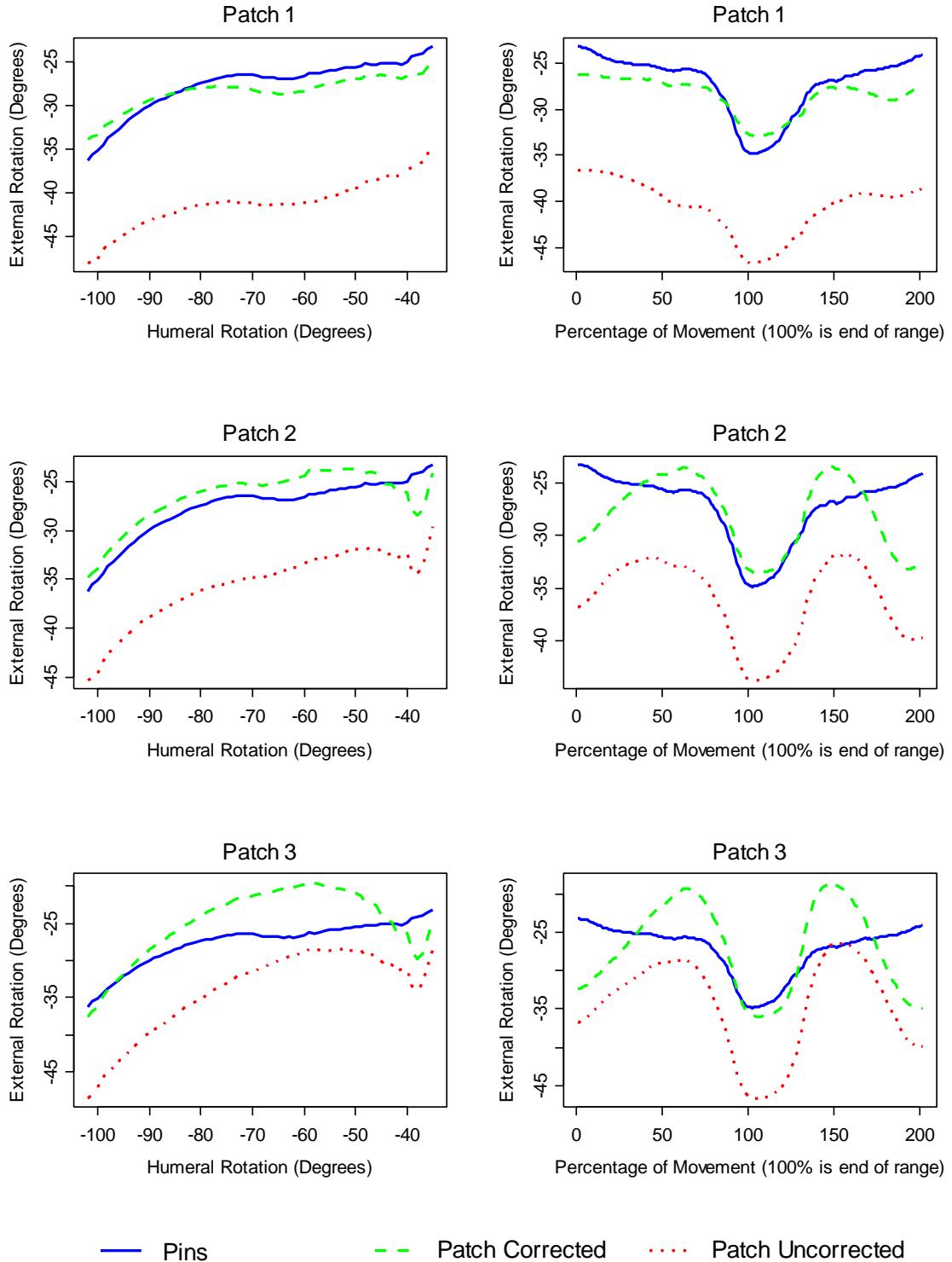


## Hand Behind Back: Pins vs. Patches Subject2 External Rotation



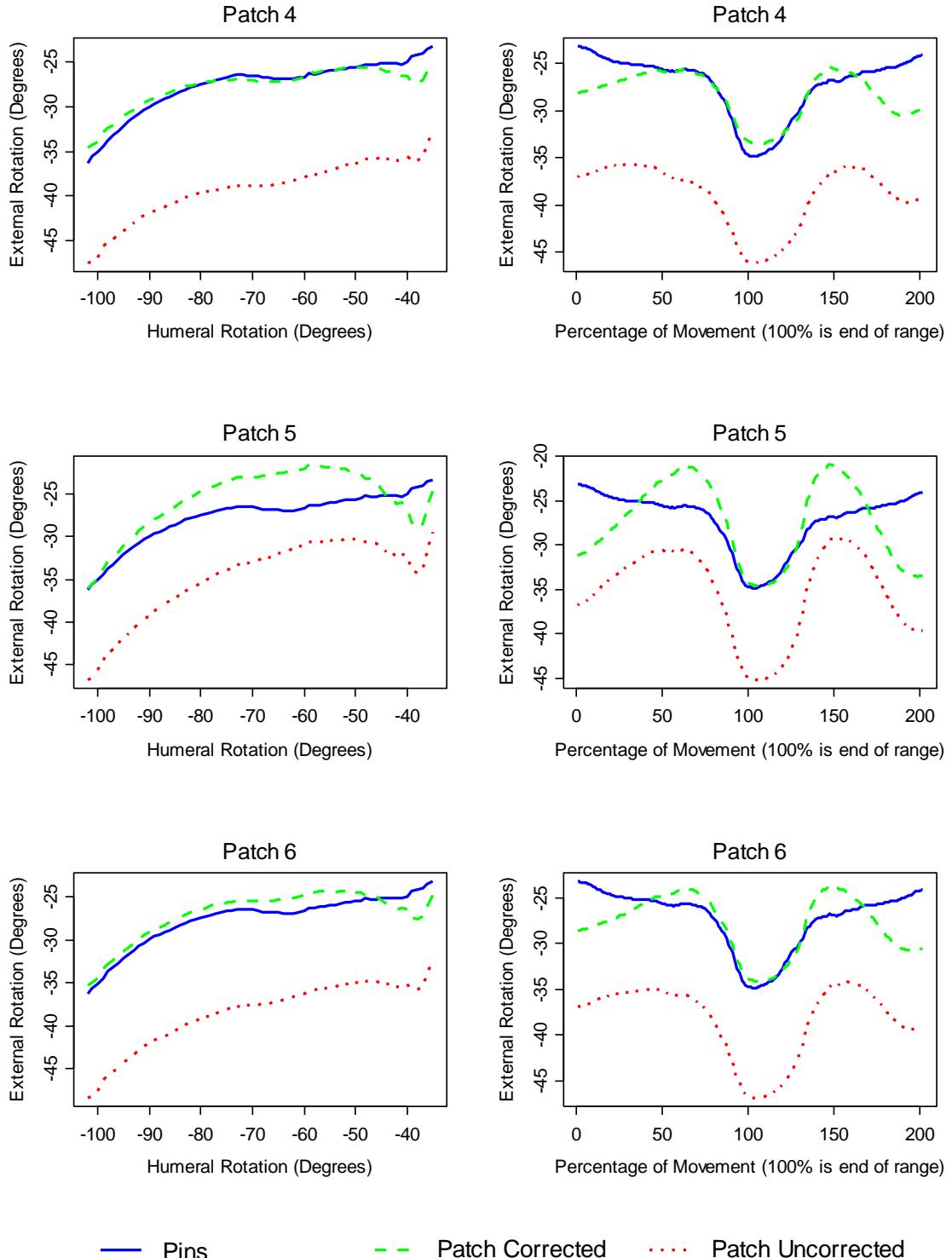
# Hand Behind Back: Pins vs. Patches Subject3

## External Rotation



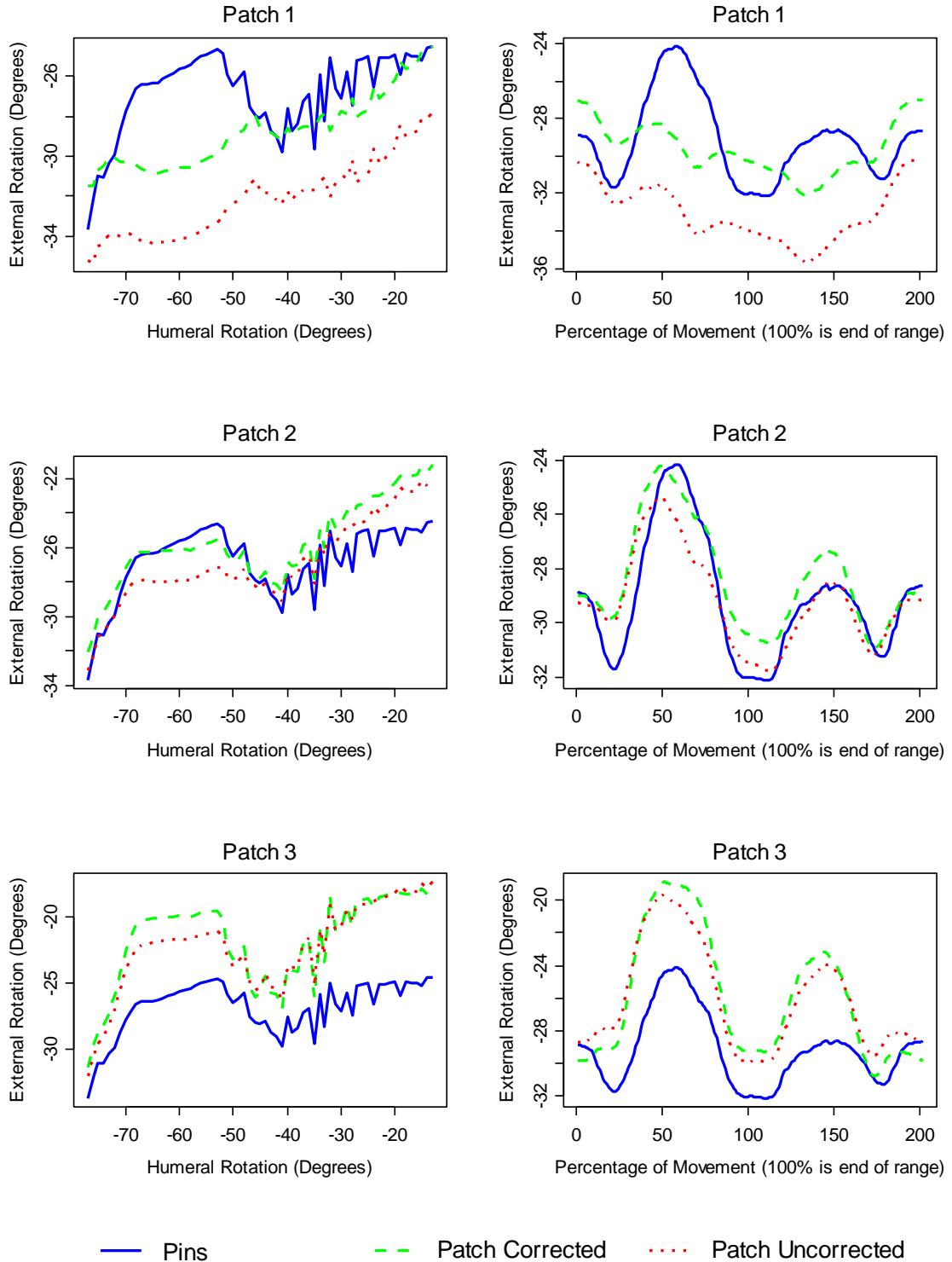
# Hand Behind Back: Pins vs. Patches Subject3

## External Rotation



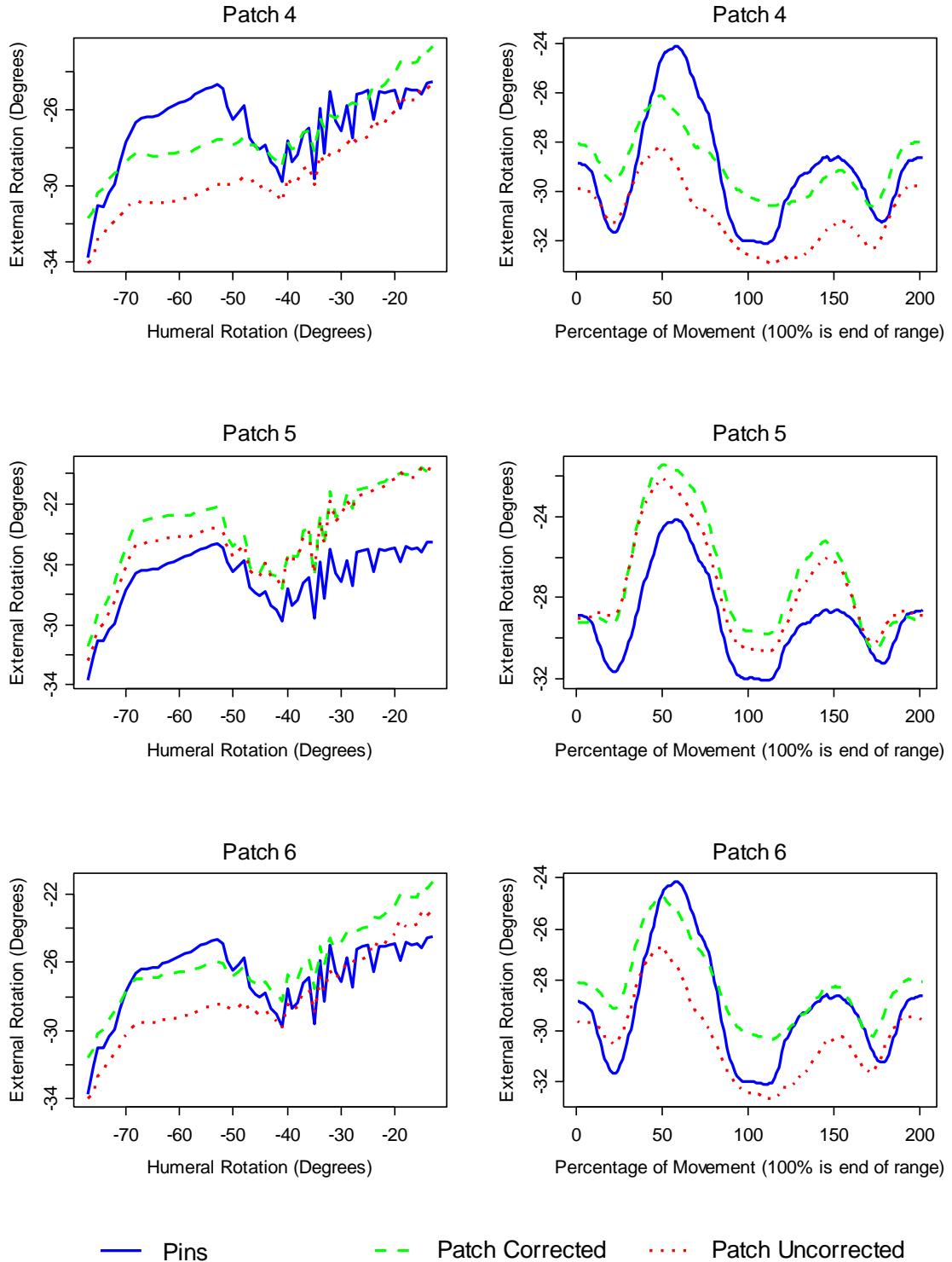
# Hand Behind Back: Pins vs. Patches Subject4

## External Rotation



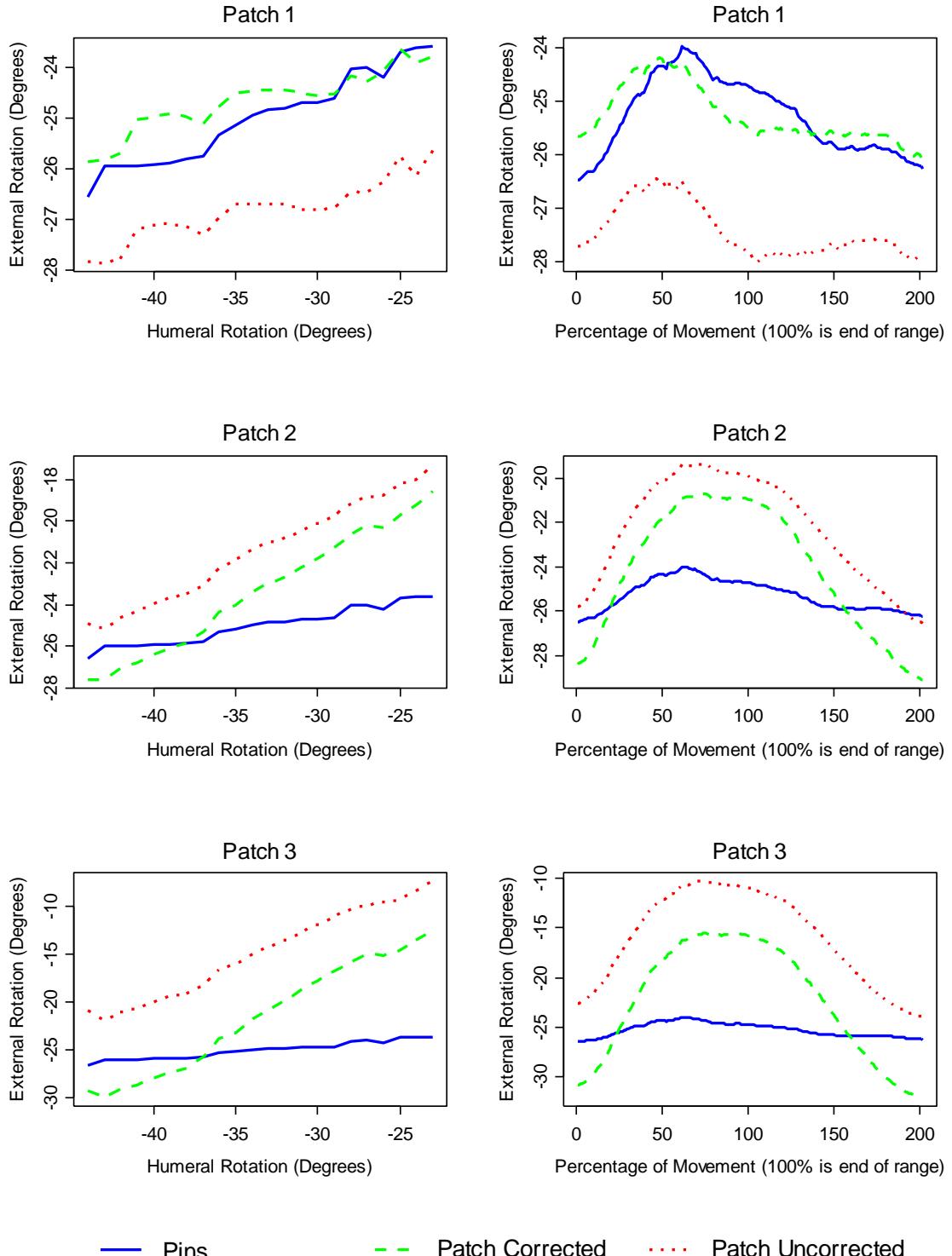
# Hand Behind Back: Pins vs. Patches Subject4

## External Rotation



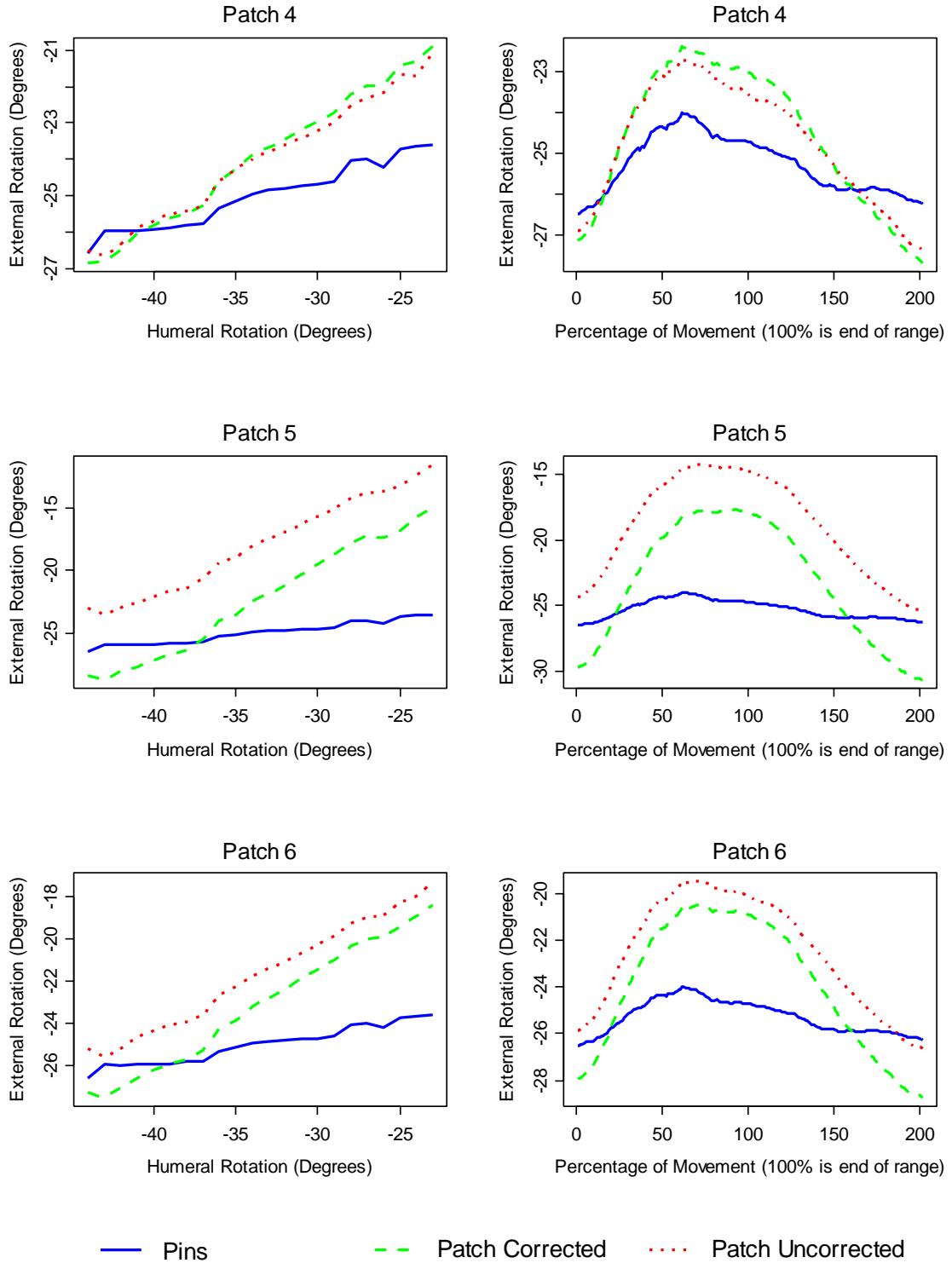
# Hand Behind Back: Pins vs. Patches Subject5

## External Rotation



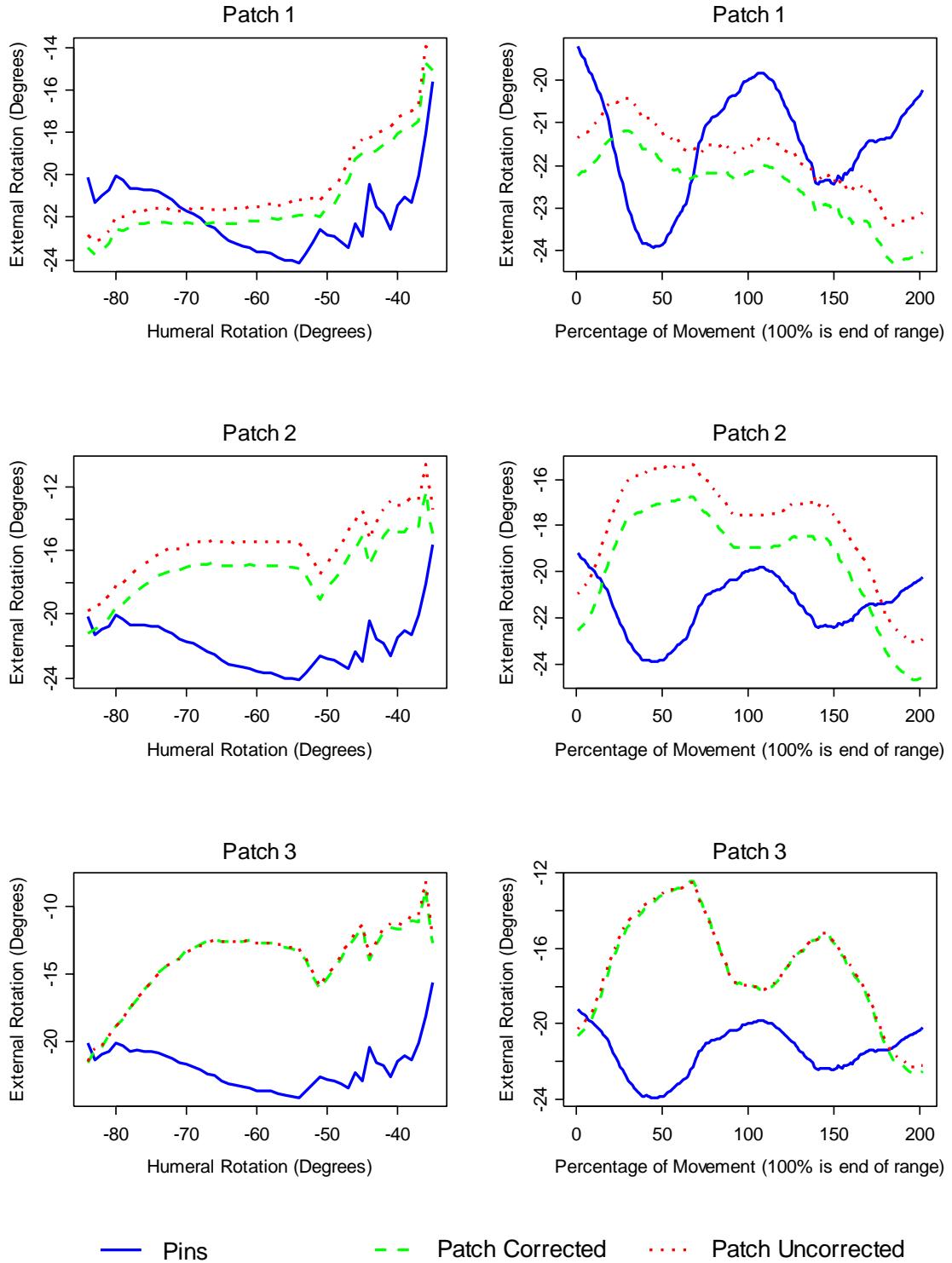
# Hand Behind Back: Pins vs. Patches Subject5

## External Rotation



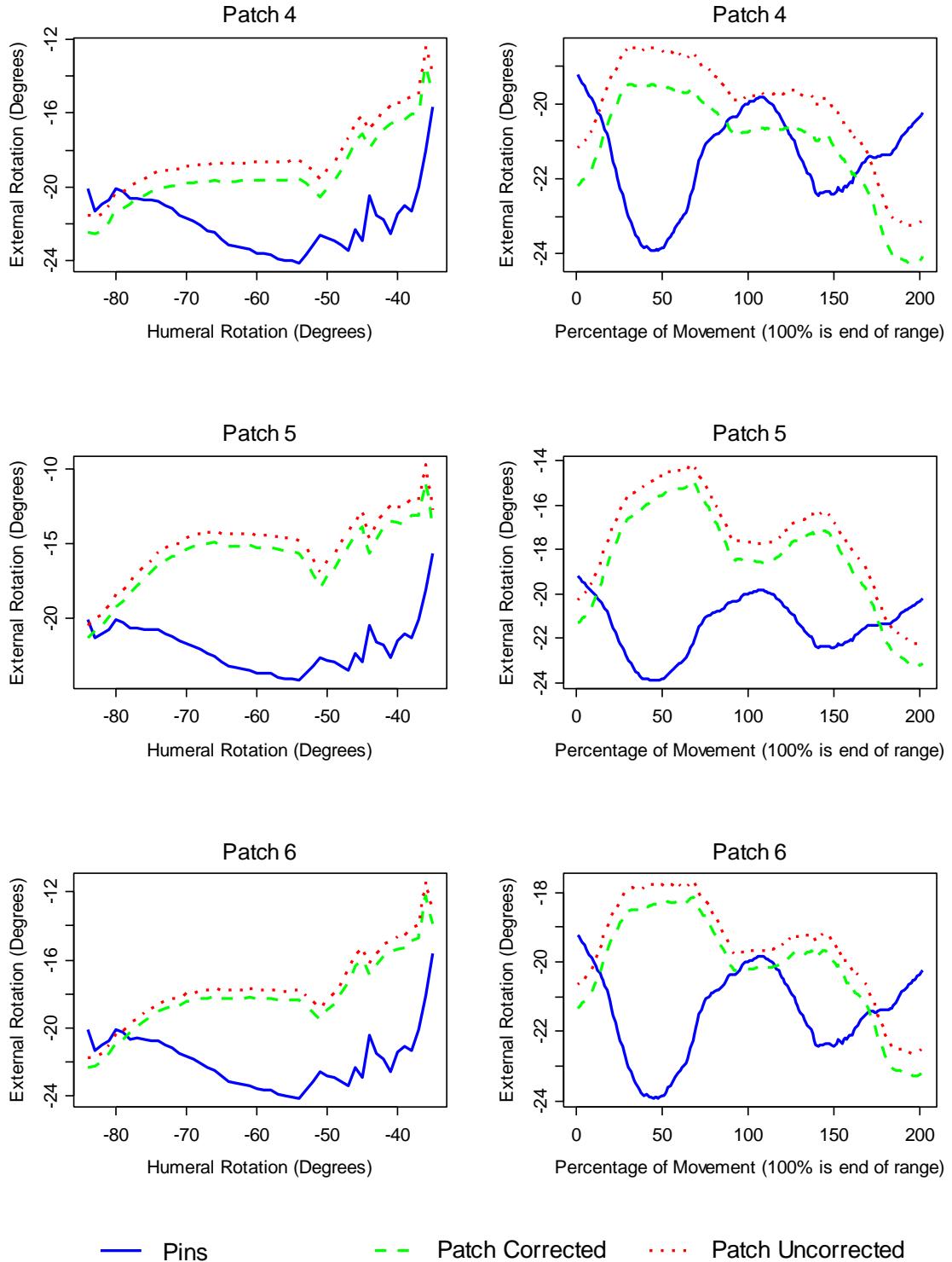
# Hand Behind Back: Pins vs. Patches Subject6

## External Rotation



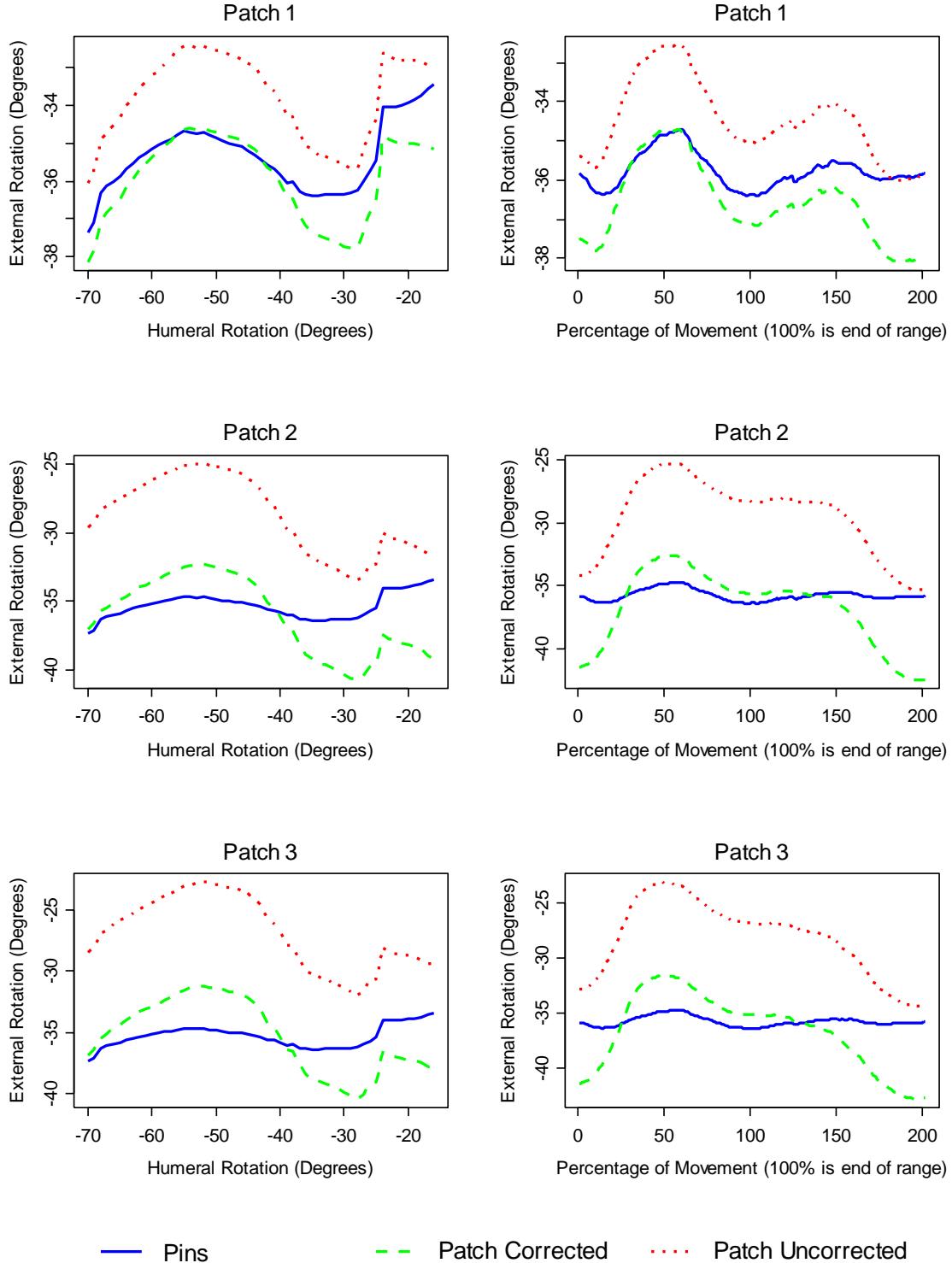
# Hand Behind Back: Pins vs. Patches Subject6

## External Rotation



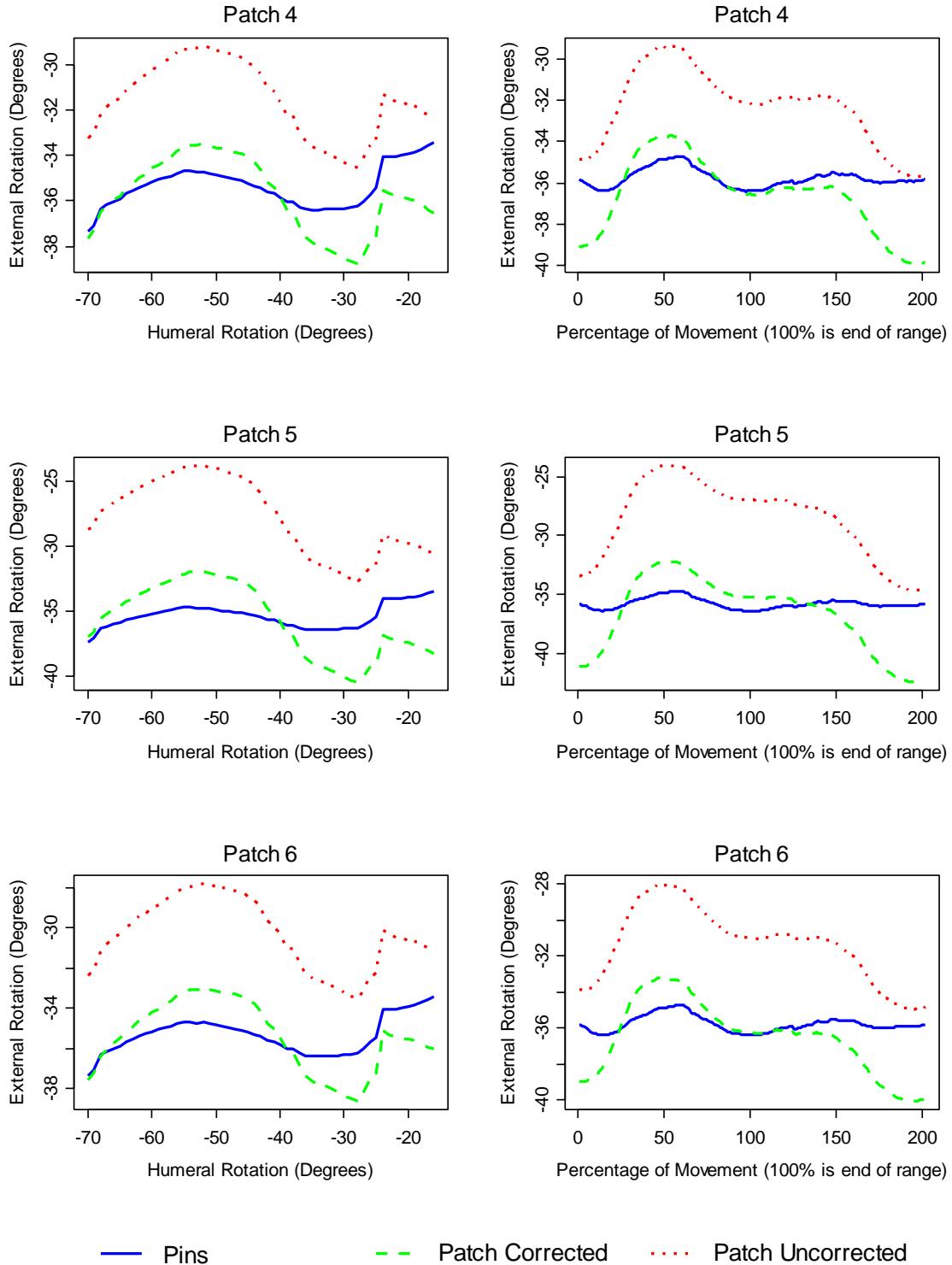
# Hand Behind Back: Pins vs. Patches Subject7

## External Rotation



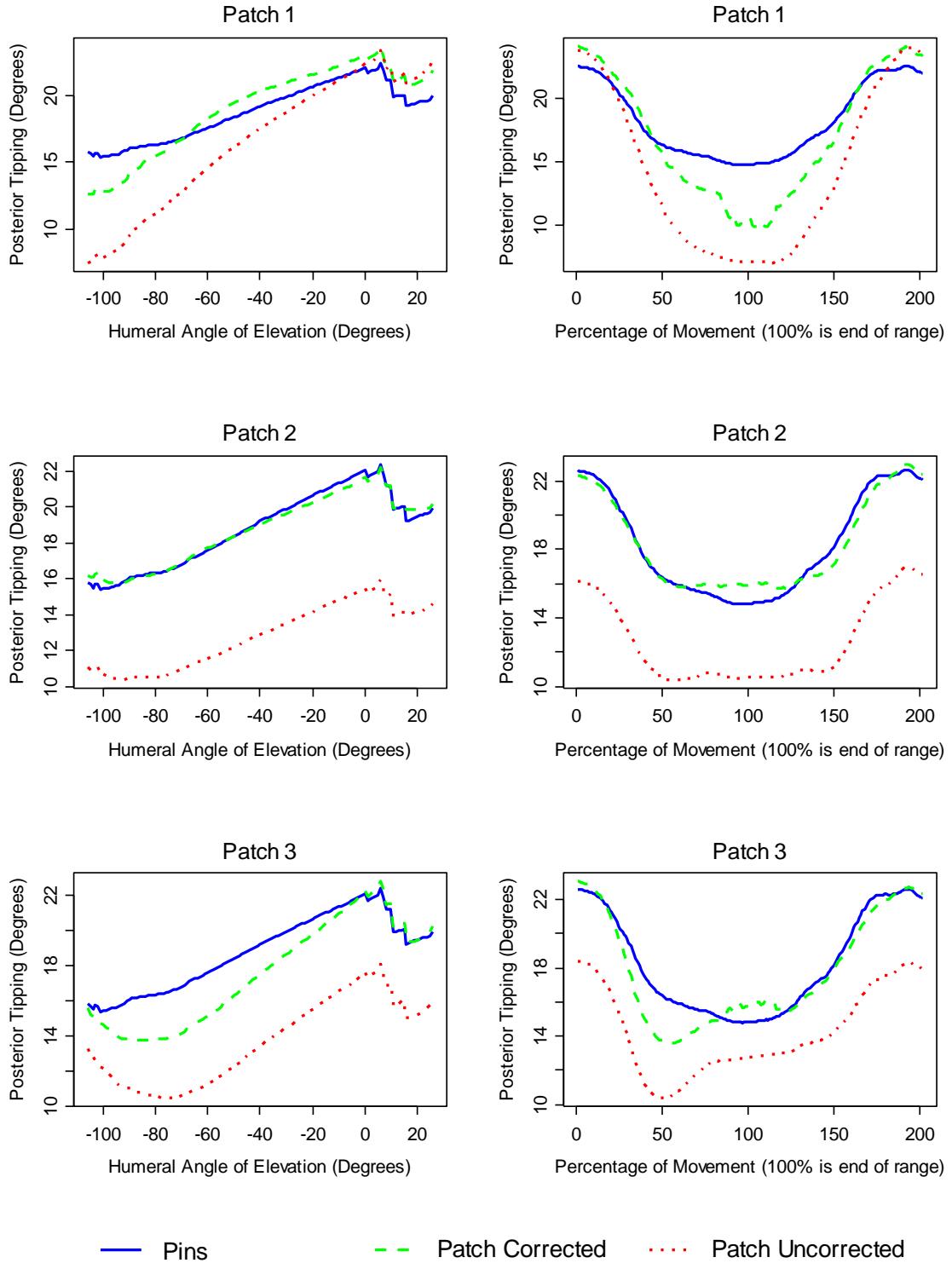
# Hand Behind Back: Pins vs. Patches Subject7

## External Rotation



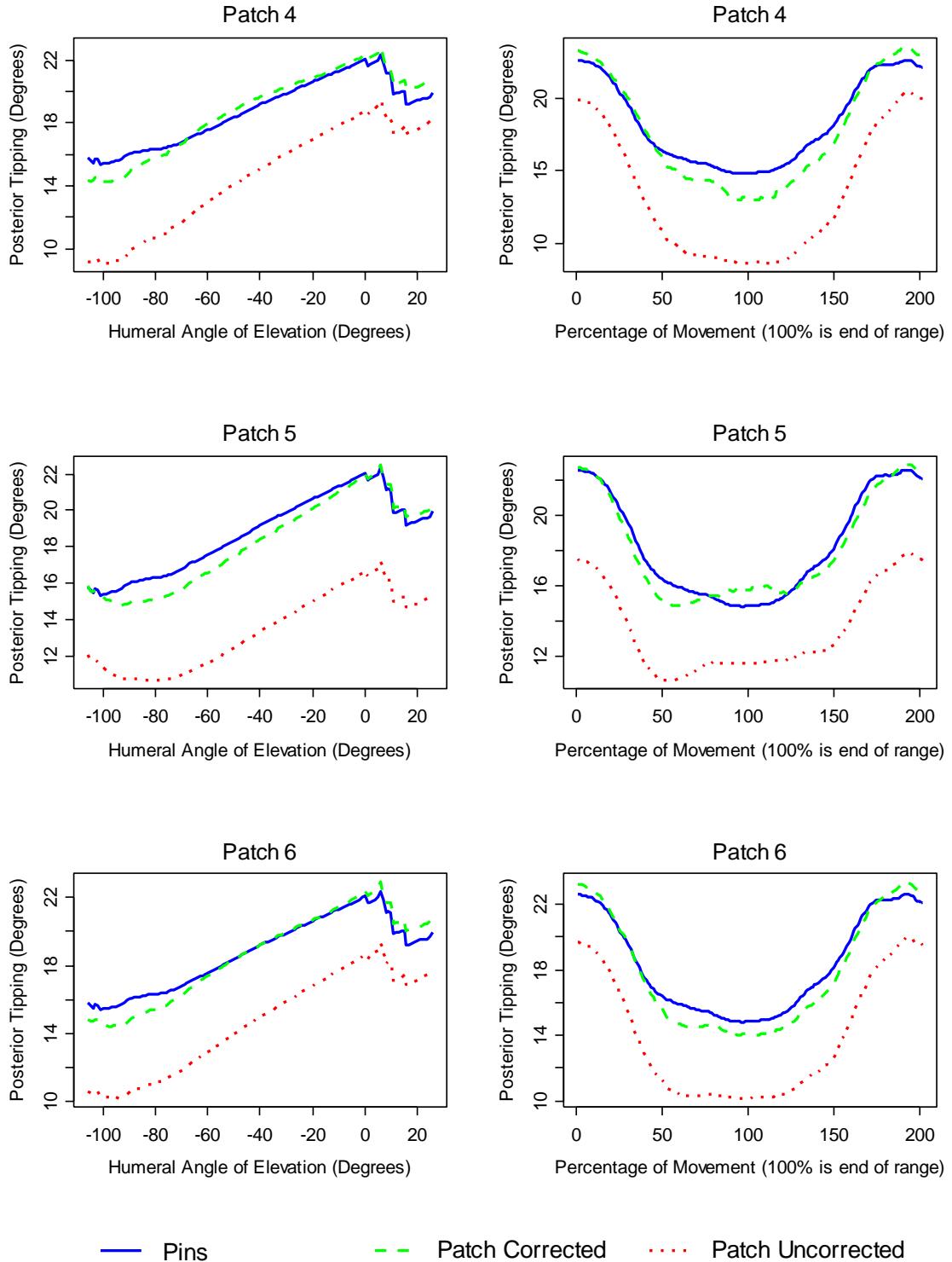
# Horizontal Adduction: Pins vs. Patches Subject1

## Posterior Tipping

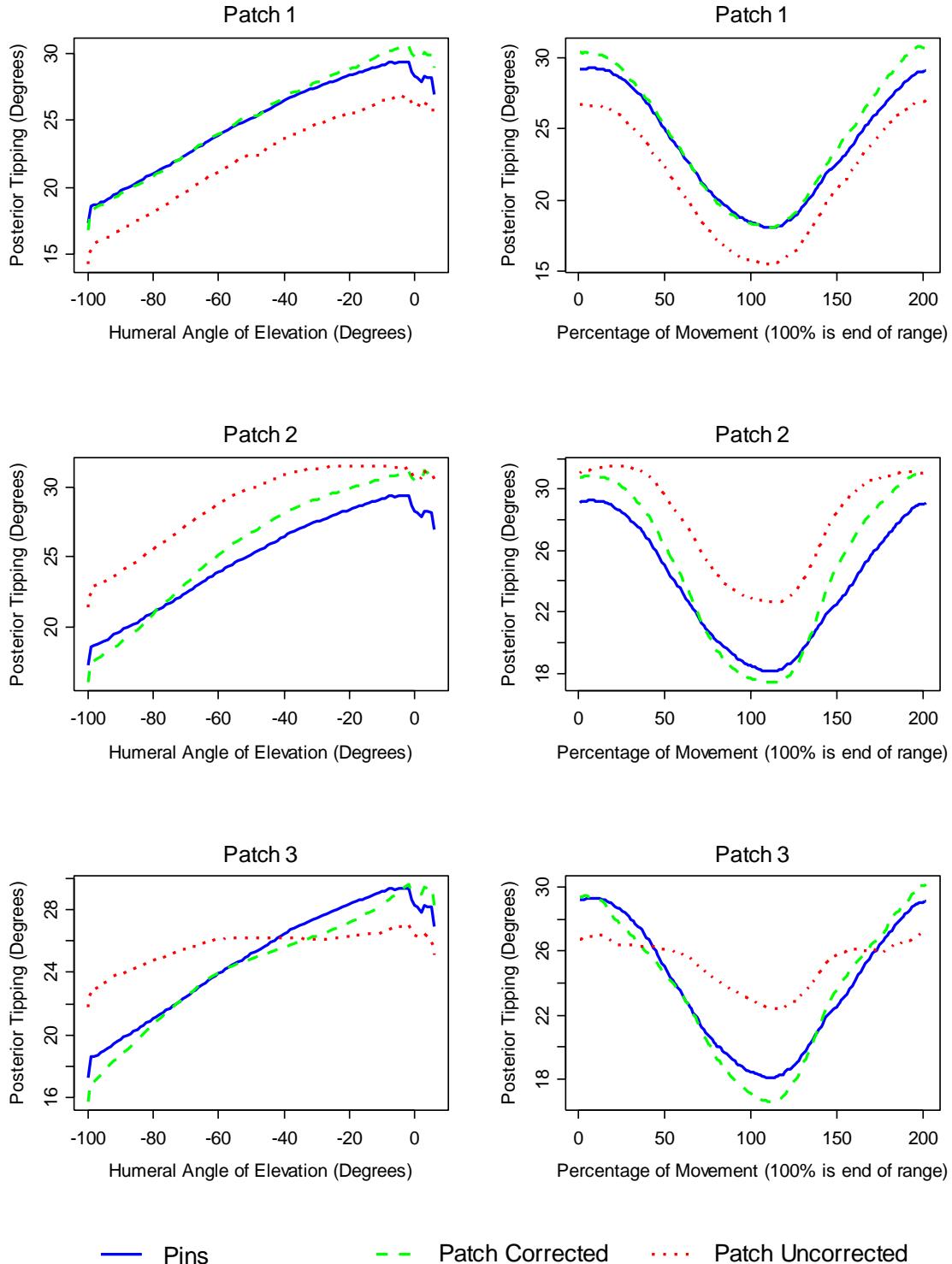


# Horizontal Adduction: Pins vs. Patches Subject1

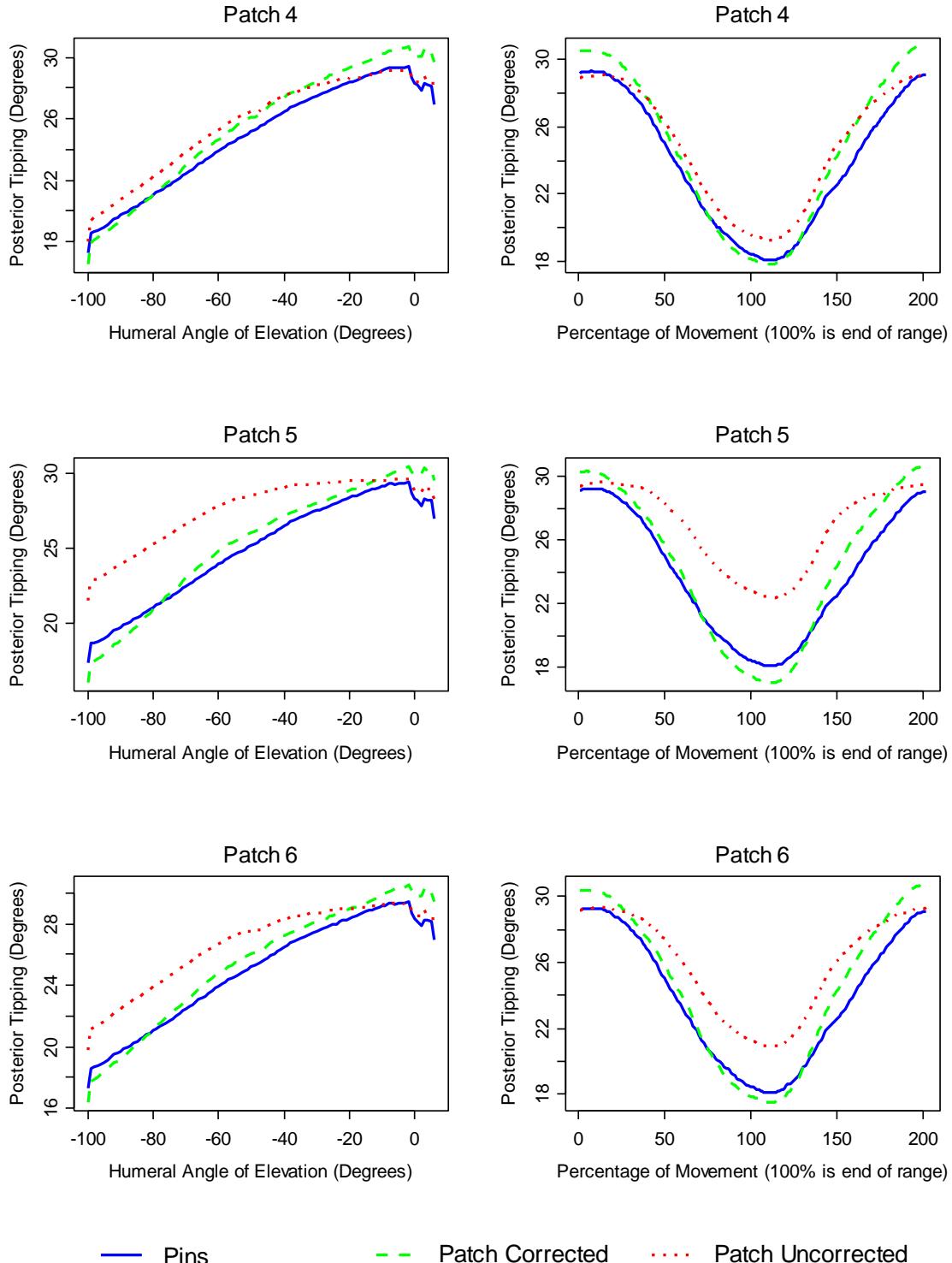
## Posterior Tipping



## Horizontal Adduction: Pins vs. Patches Subject2 Posterior Tipping

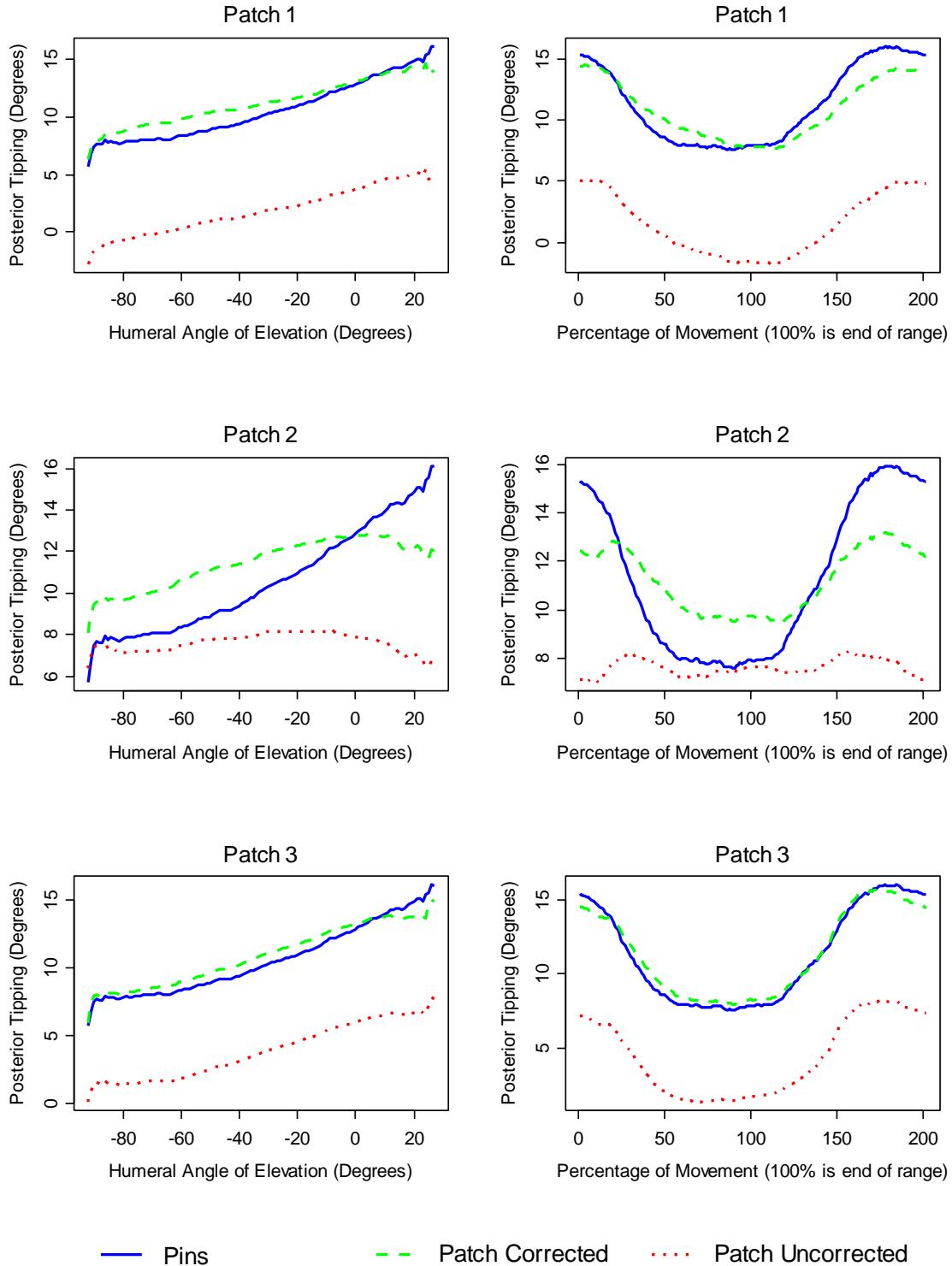


## Horizontal Adduction: Pins vs. Patches Subject2 Posterior Tipping



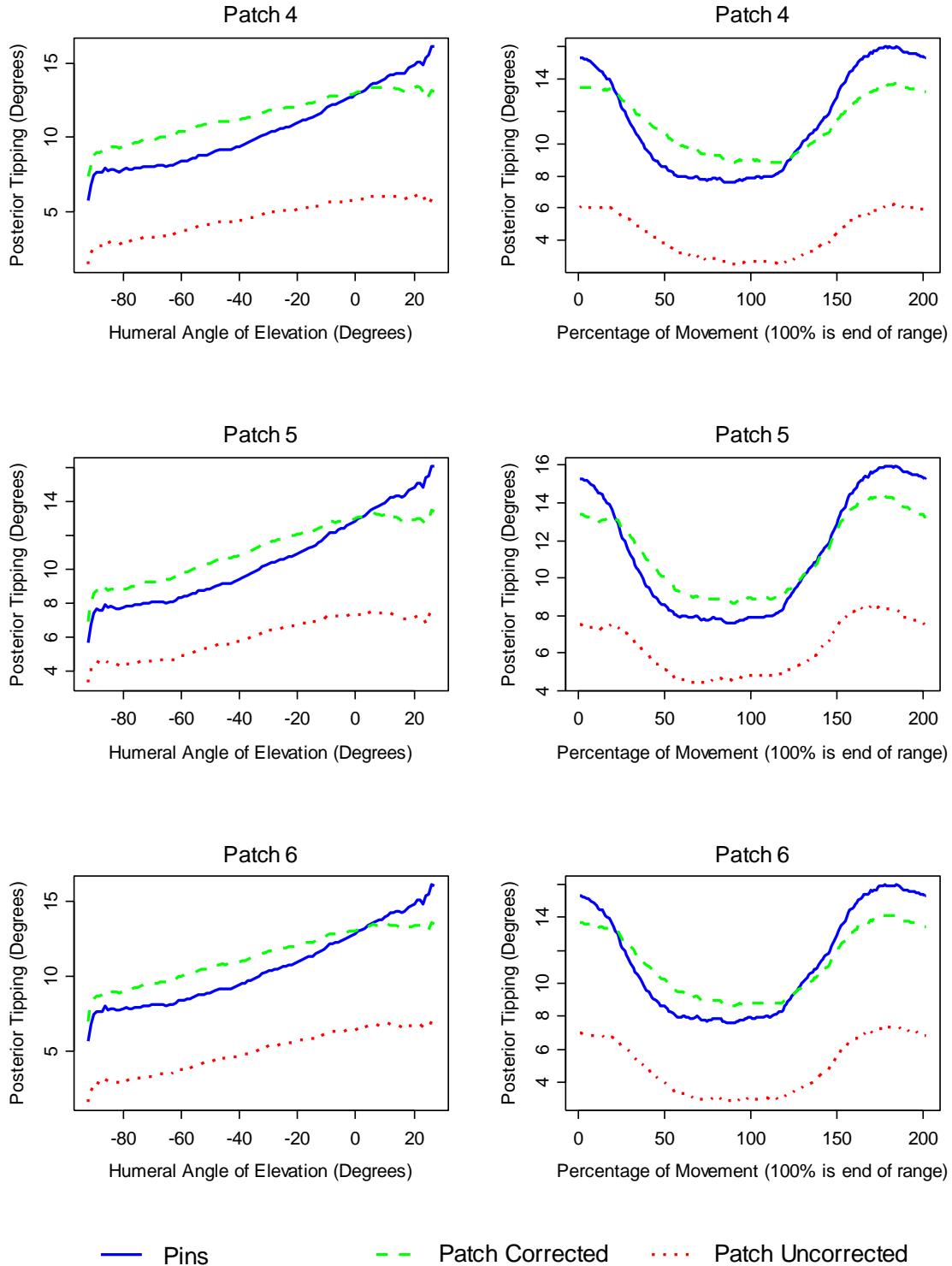
# Horizontal Adduction: Pins vs. Patches Subject3

## Posterior Tipping



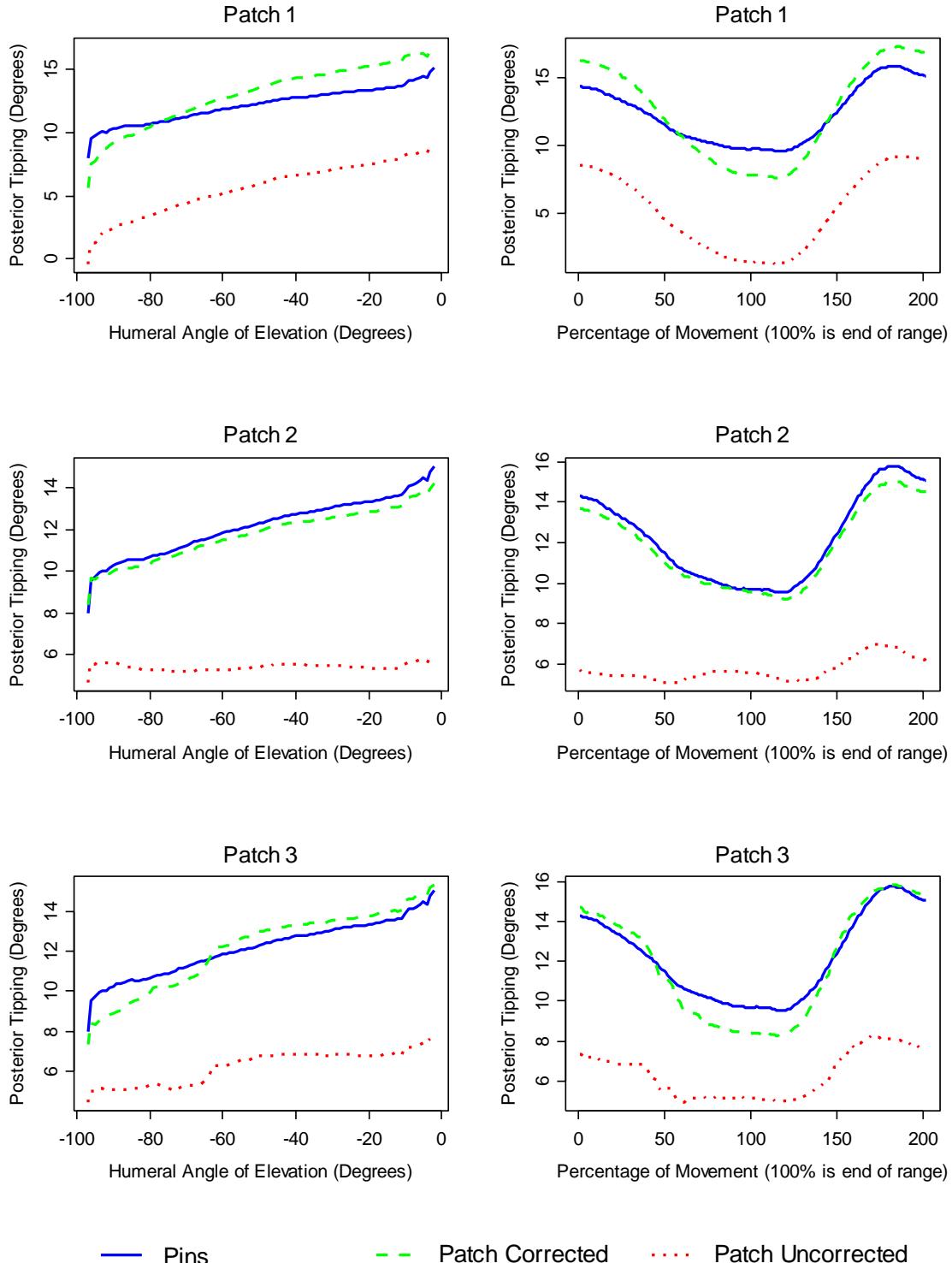
# Horizontal Adduction: Pins vs. Patches Subject3

## Posterior Tipping



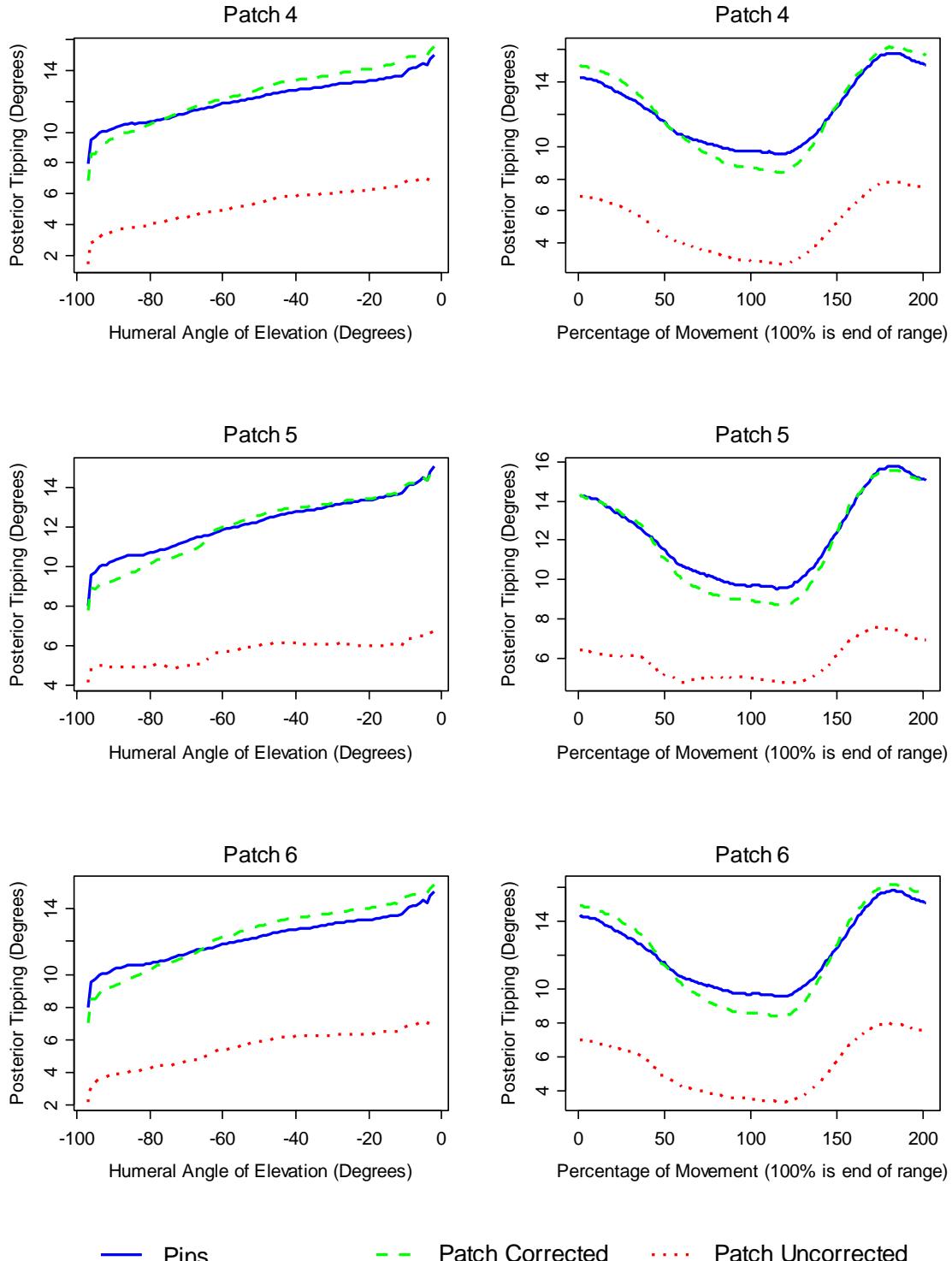
# Horizontal Adduction: Pins vs. Patches Subject4

## Posterior Tipping



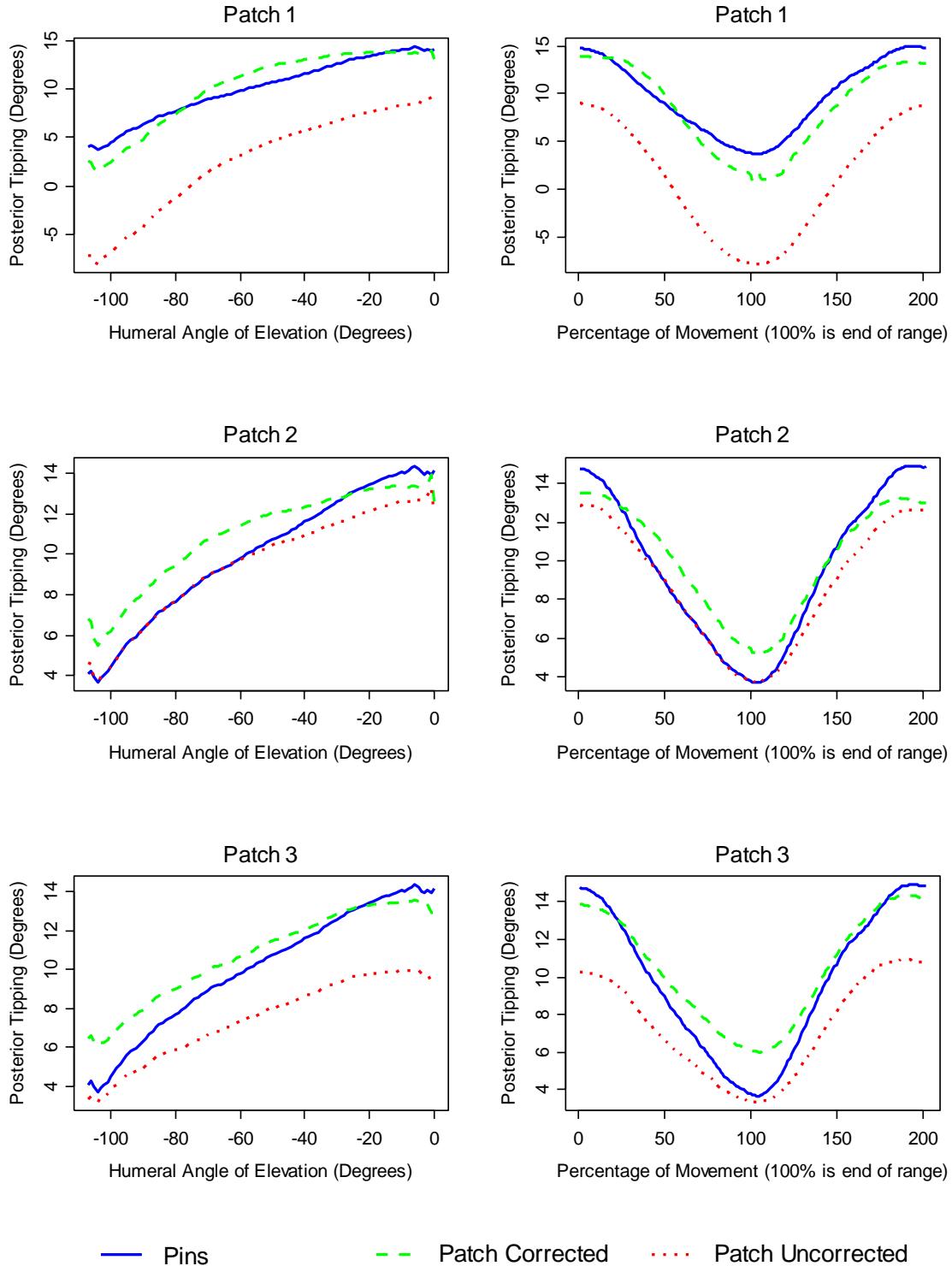
# Horizontal Adduction: Pins vs. Patches Subject4

## Posterior Tipping



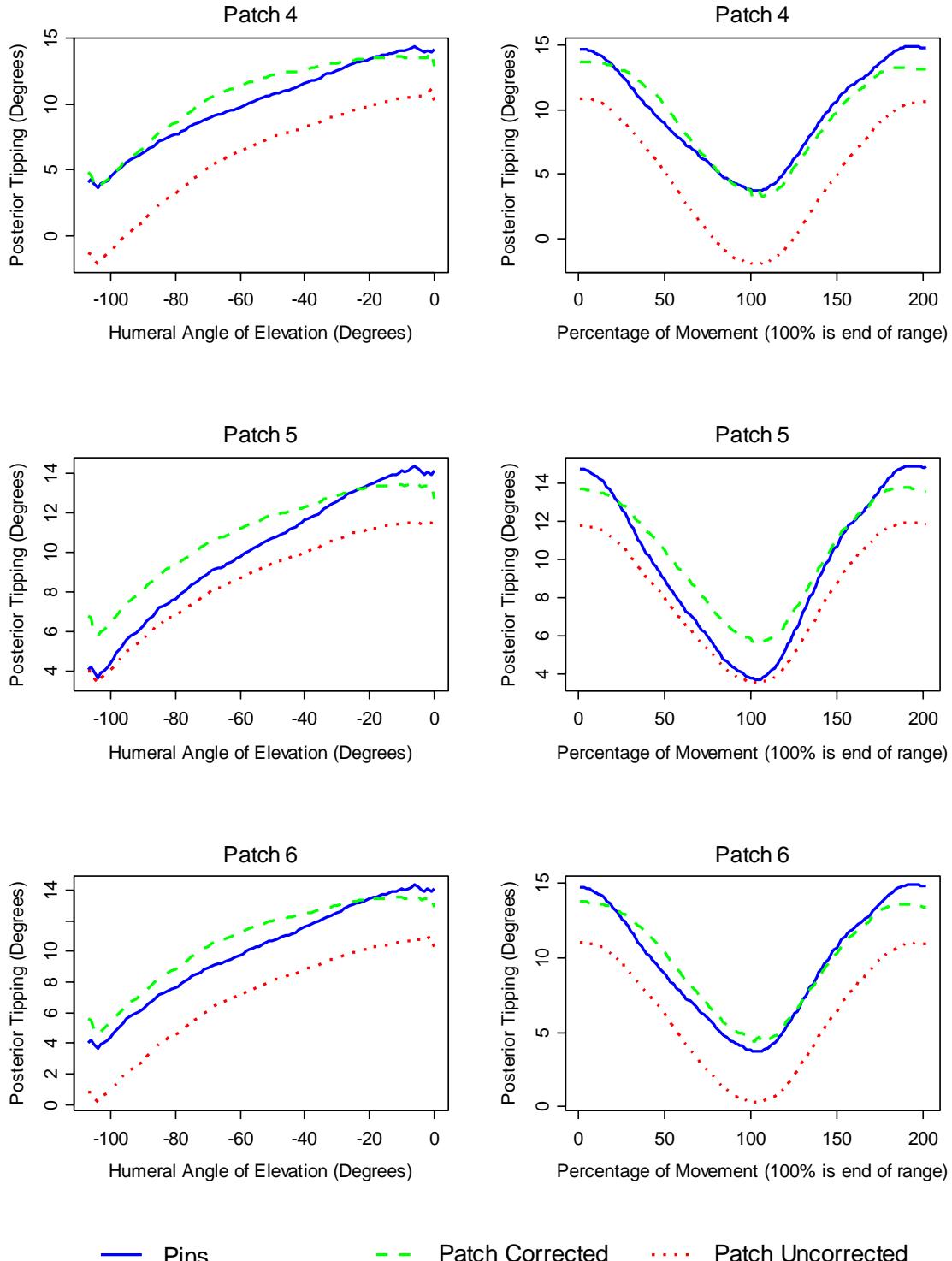
# Horizontal Adduction: Pins vs. Patches Subject5

## Posterior Tipping



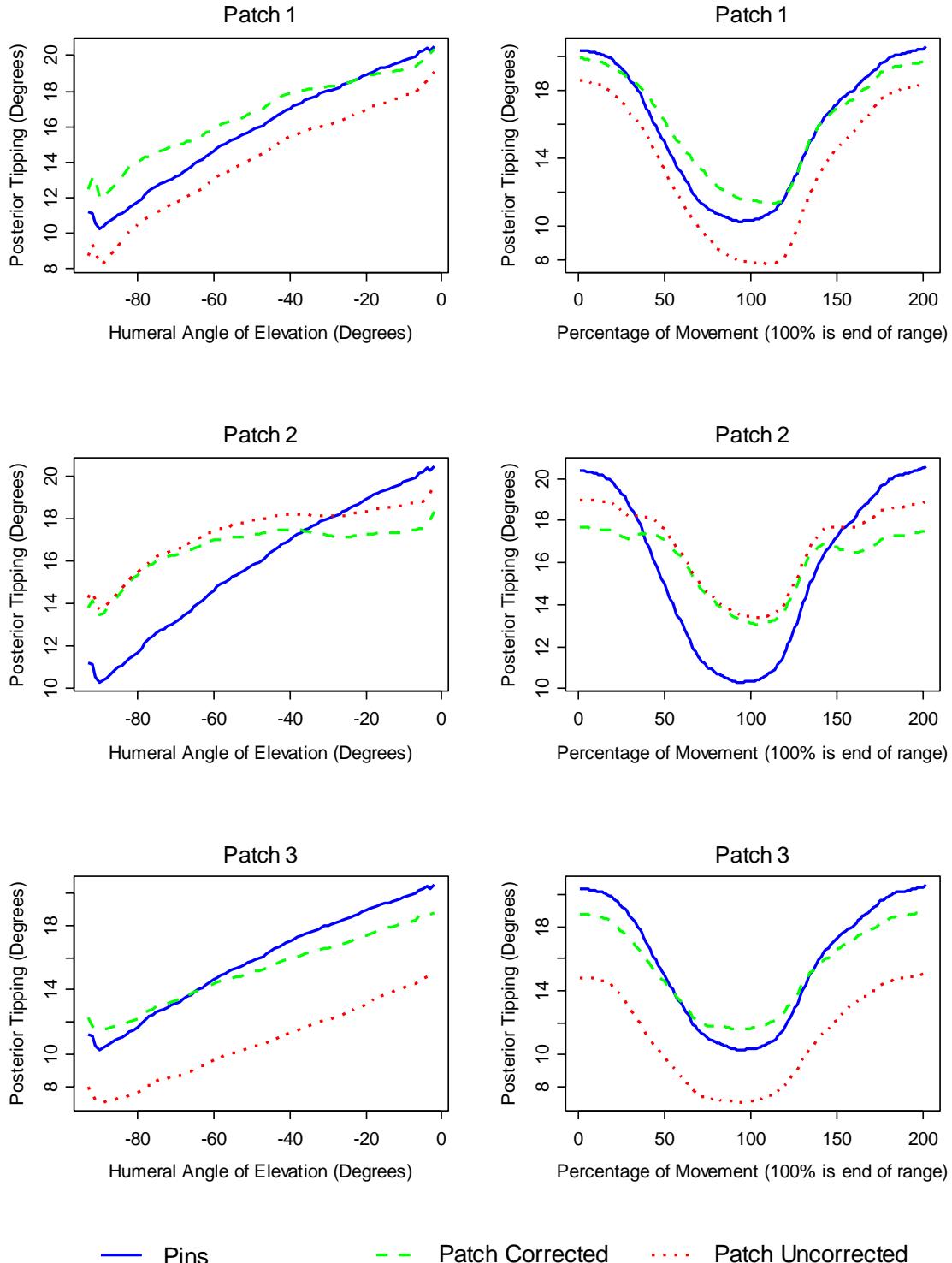
# Horizontal Adduction: Pins vs. Patches Subject5

## Posterior Tipping



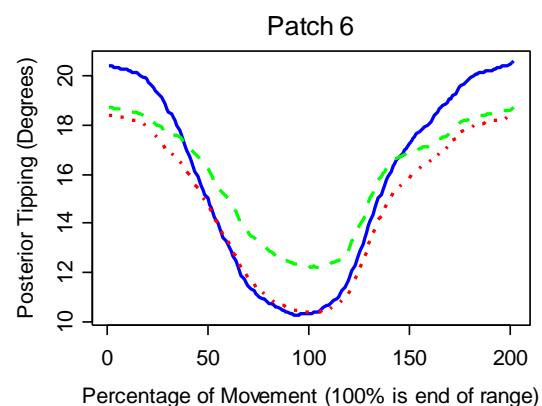
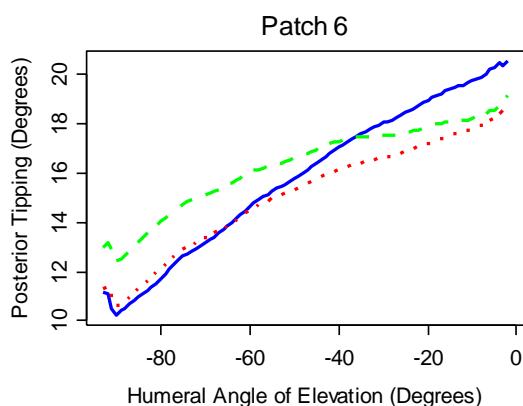
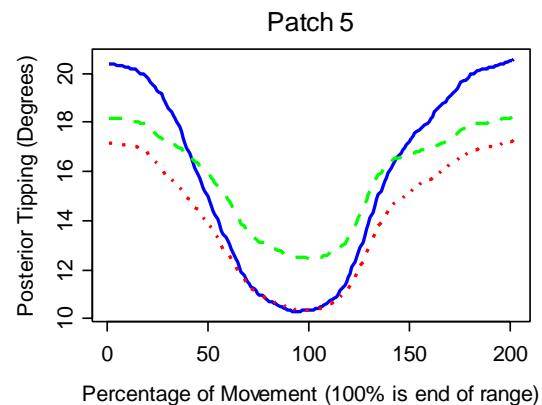
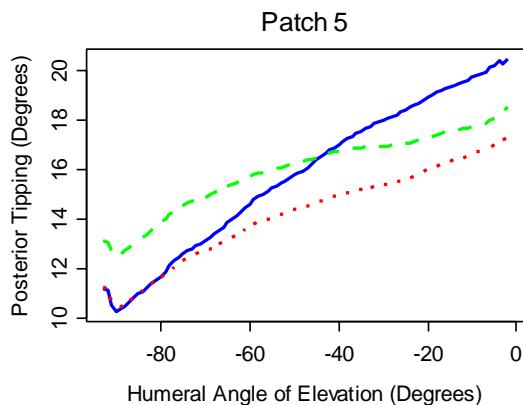
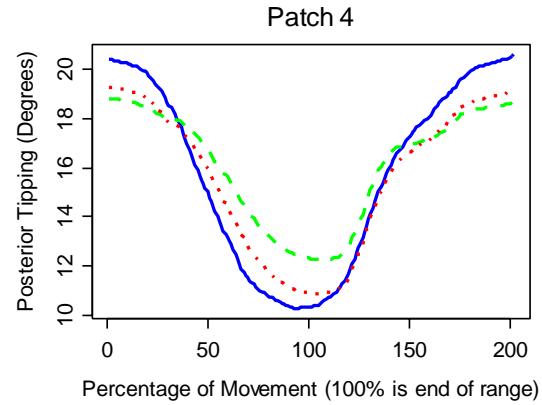
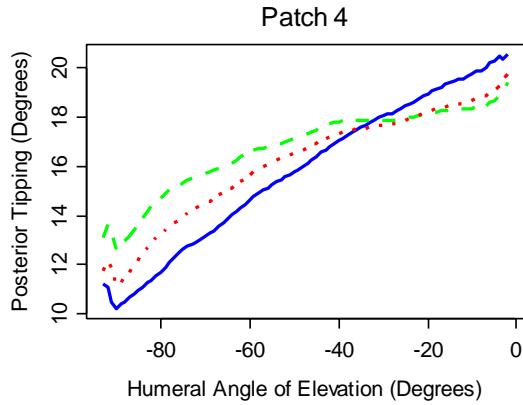
# Horizontal Adduction: Pins vs. Patches Subject6

## Posterior Tipping



# Horizontal Adduction: Pins vs. Patches Subject6

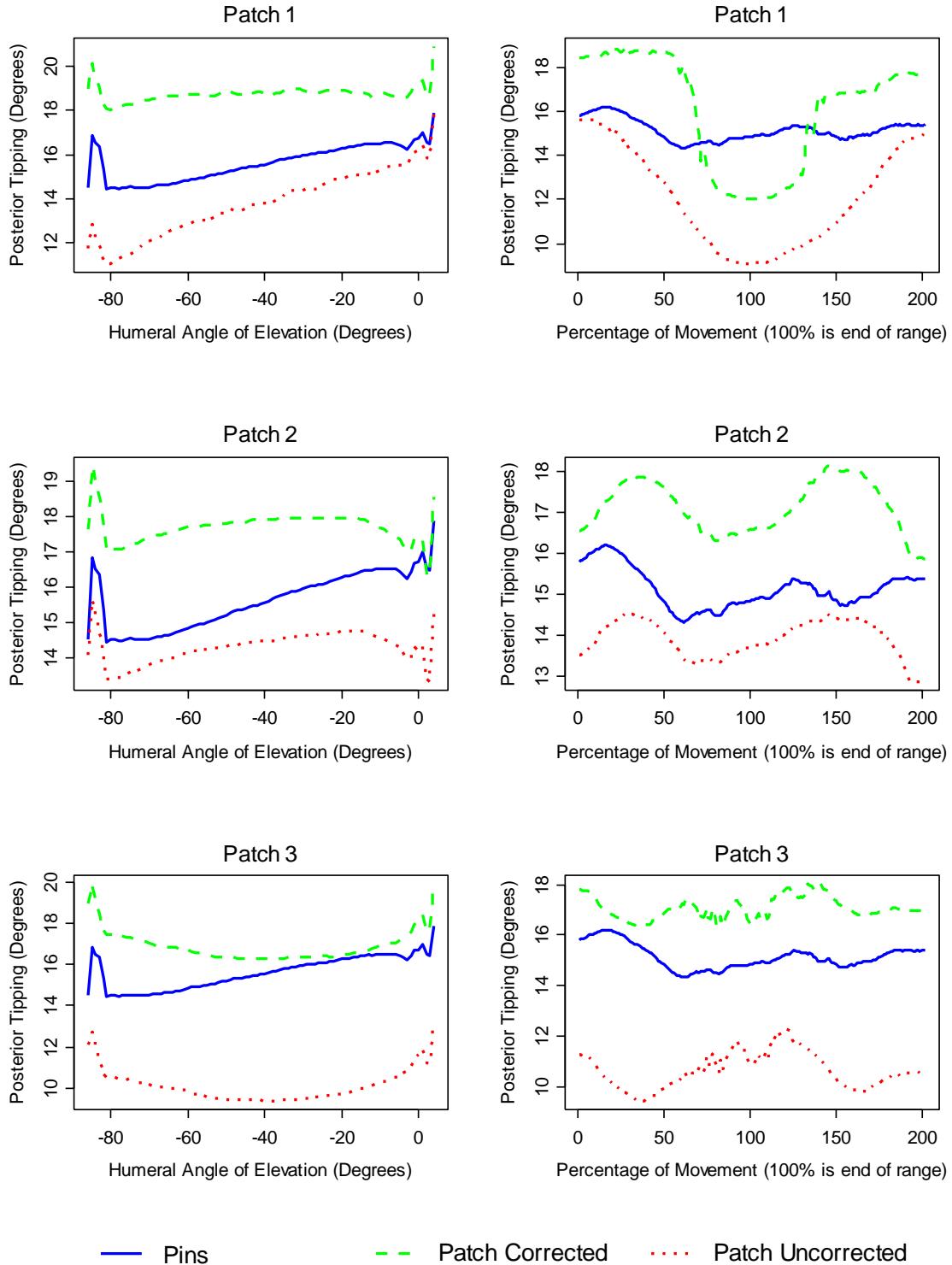
## Posterior Tipping



— Pins      - - - Patch Corrected      ····· Patch Uncorrected

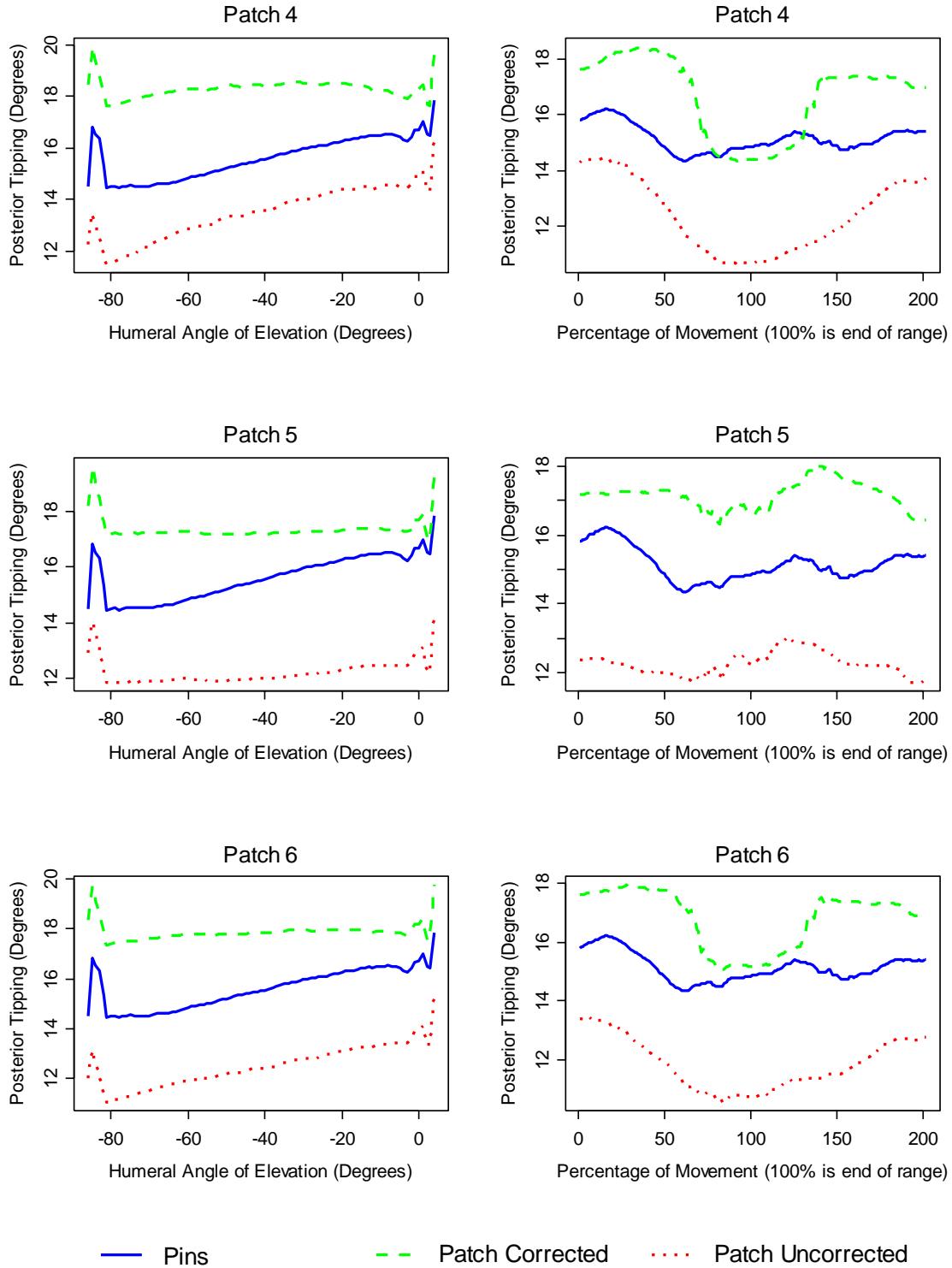
# Horizontal Adduction: Pins vs. Patches Subject7

## Posterior Tipping



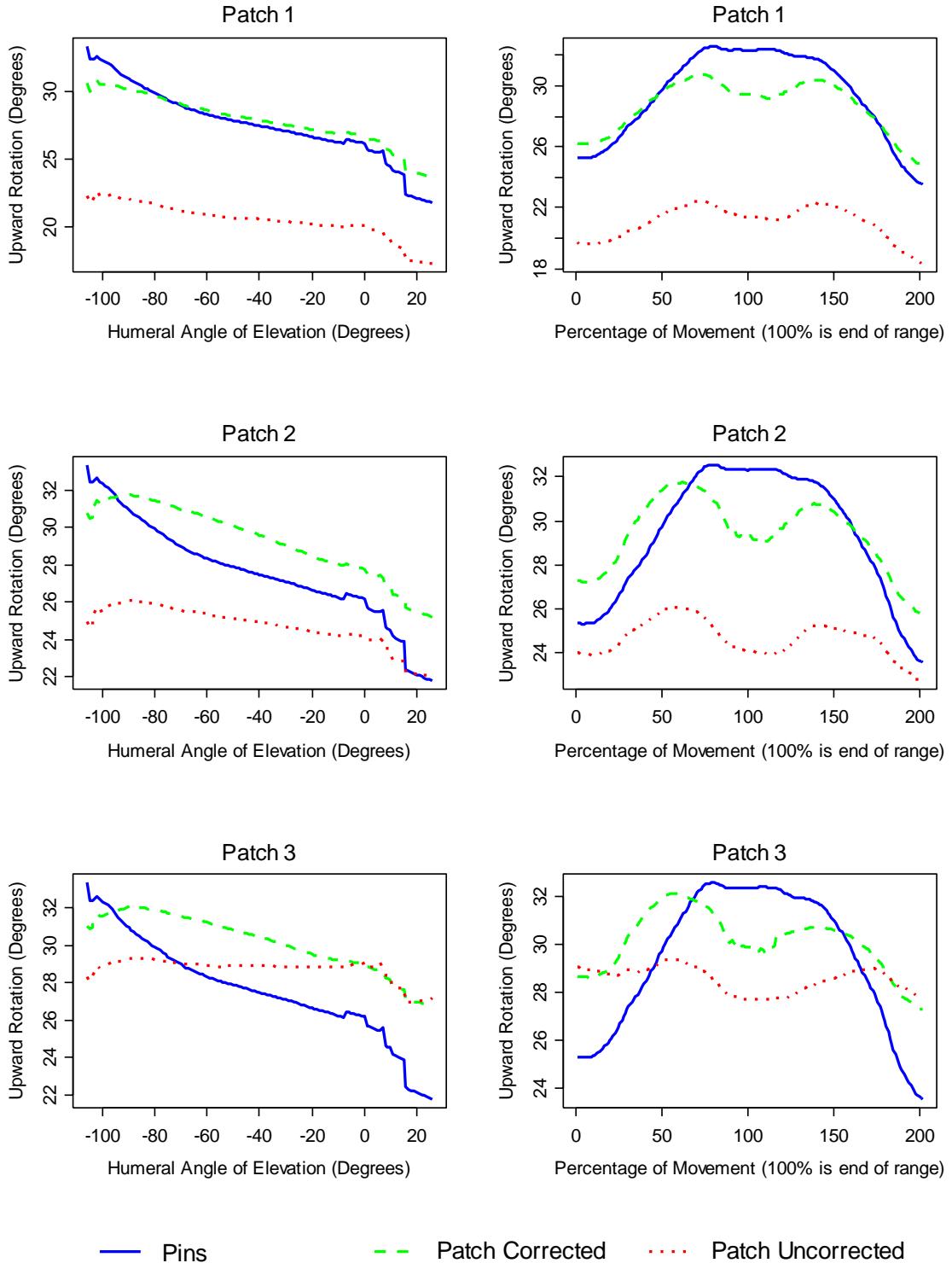
# Horizontal Adduction: Pins vs. Patches Subject7

## Posterior Tipping



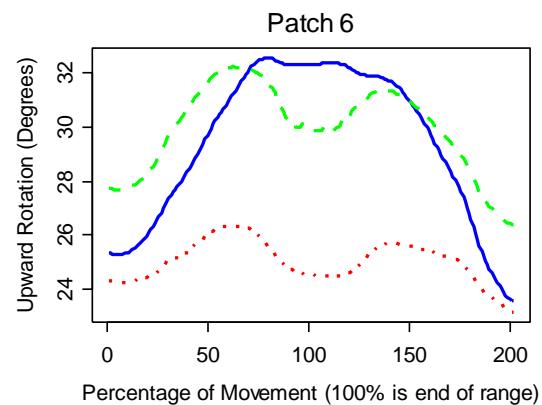
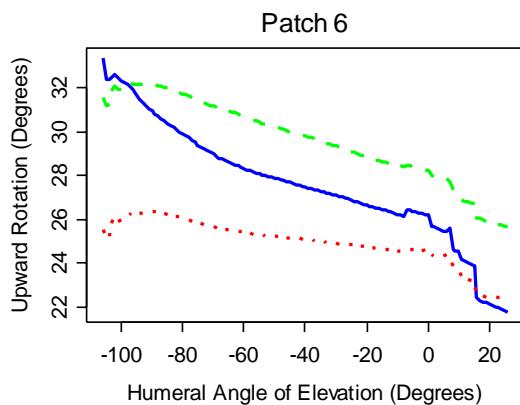
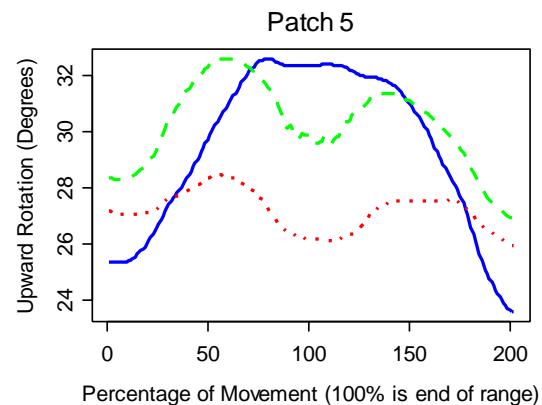
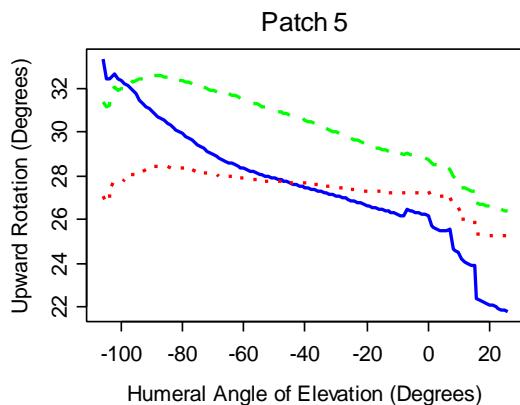
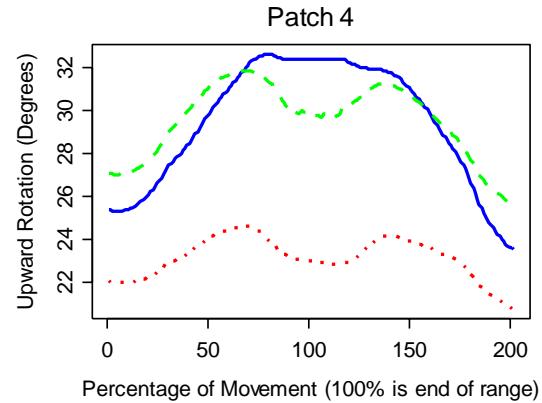
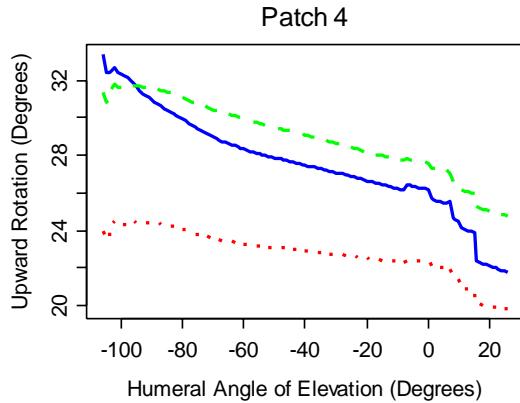
# Horizontal Adduction: Pins vs. Patches Subject1

## Upward Rotation



# Horizontal Adduction: Pins vs. Patches Subject1

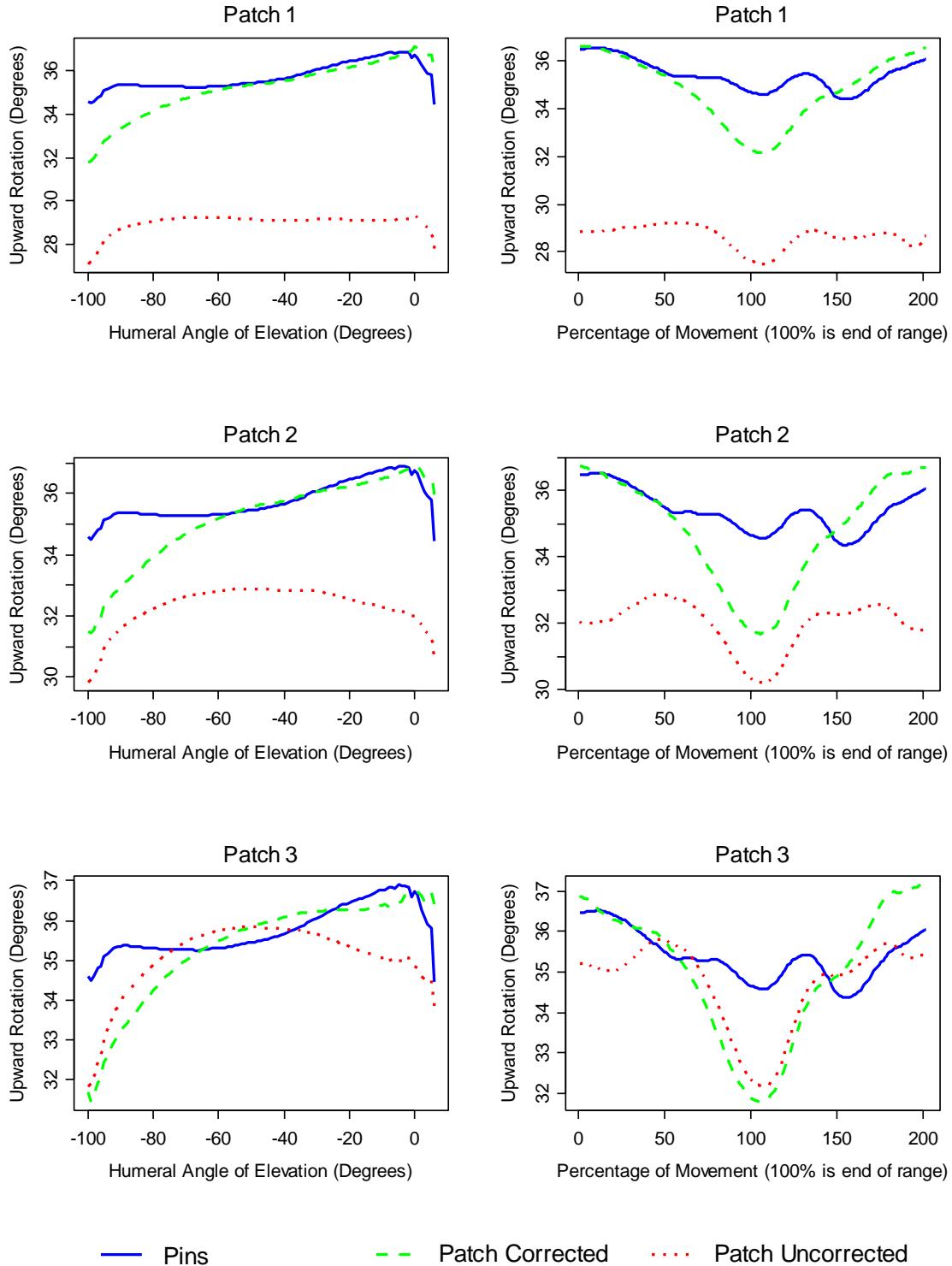
## Upward Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

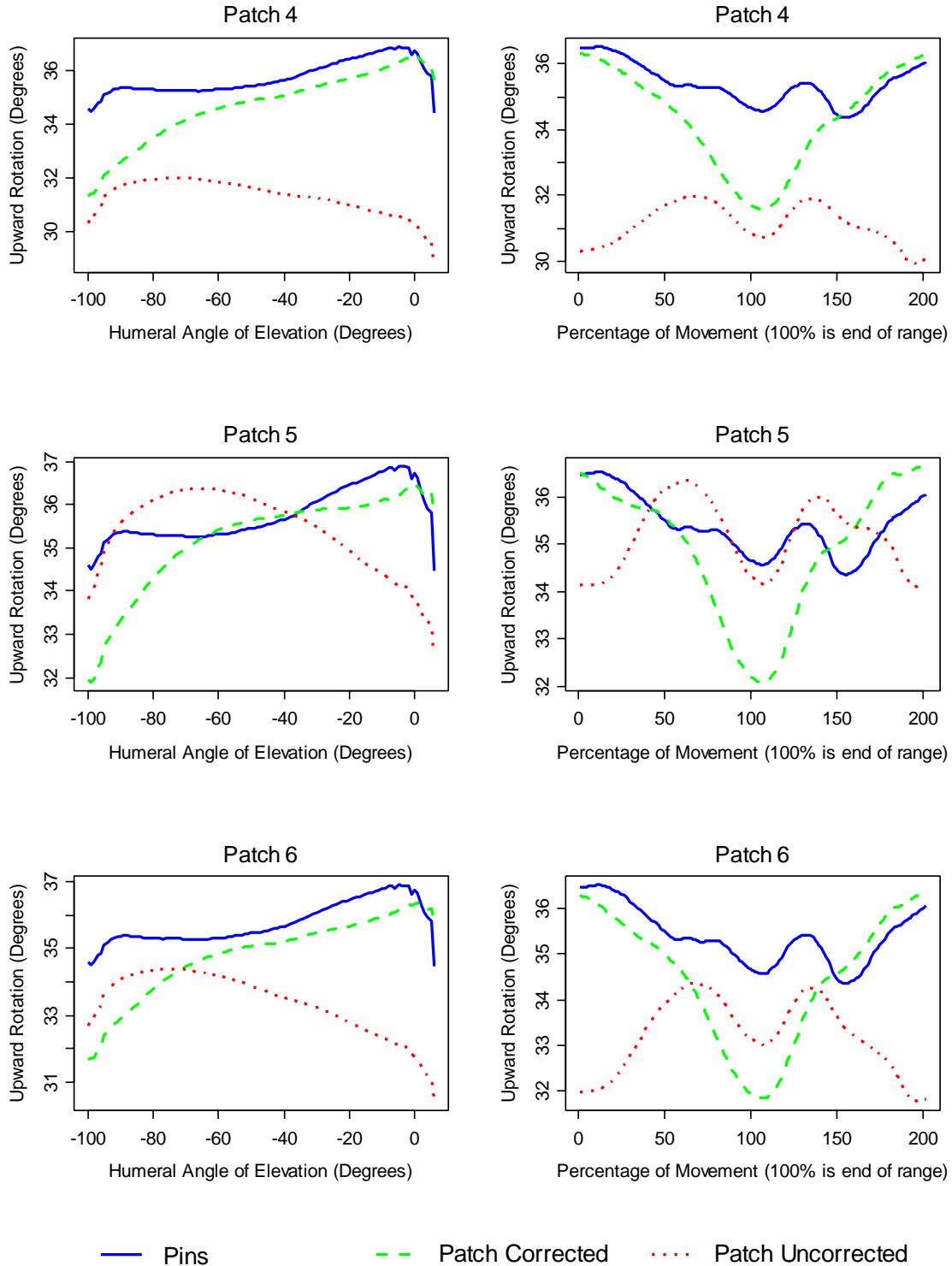
## Horizontal Adduction: Pins vs. Patches Subject2

### Upward Rotation



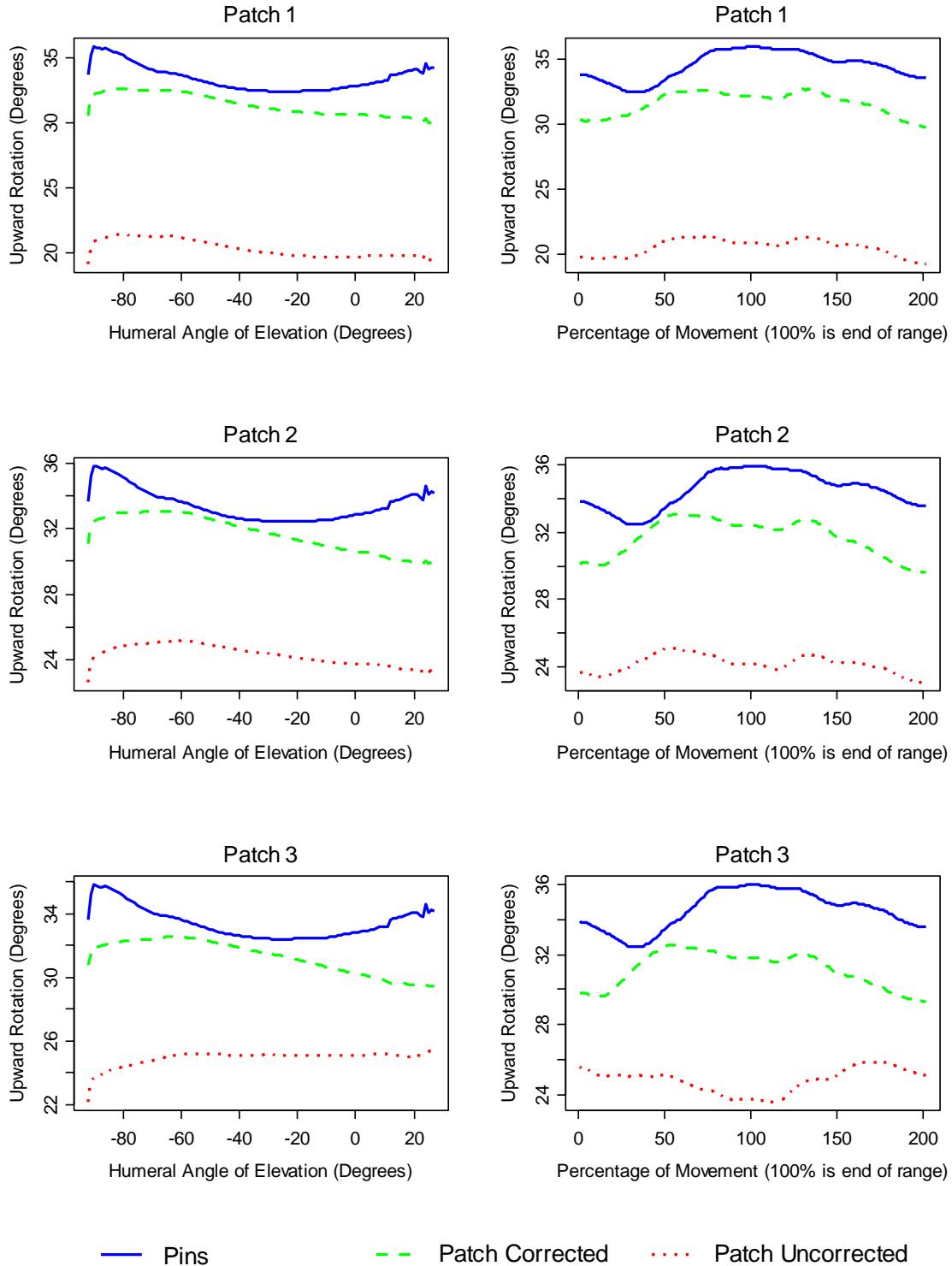
## Horizontal Adduction: Pins vs. Patches Subject2

### Upward Rotation



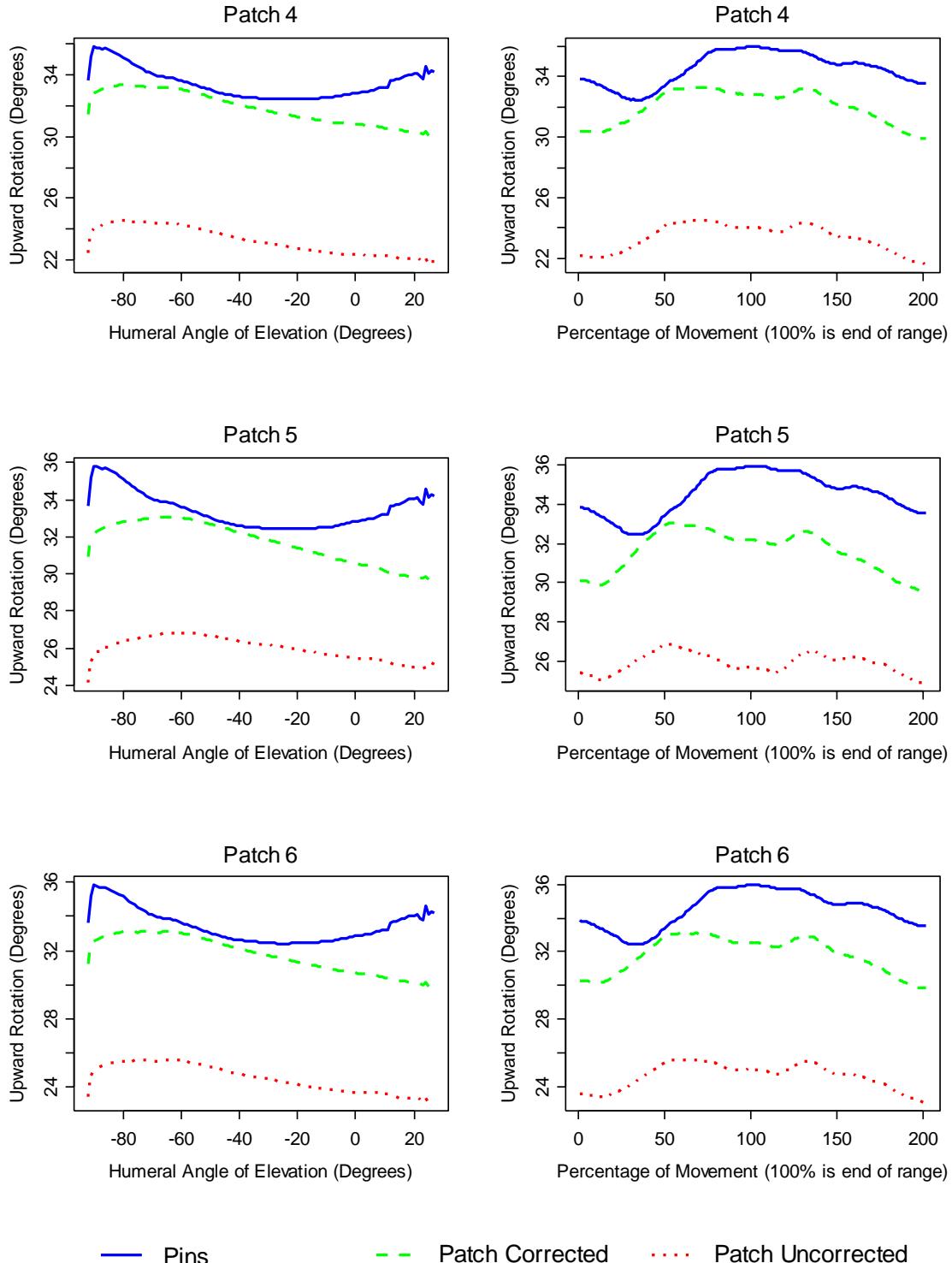
# Horizontal Adduction: Pins vs. Patches Subject3

## Upward Rotation



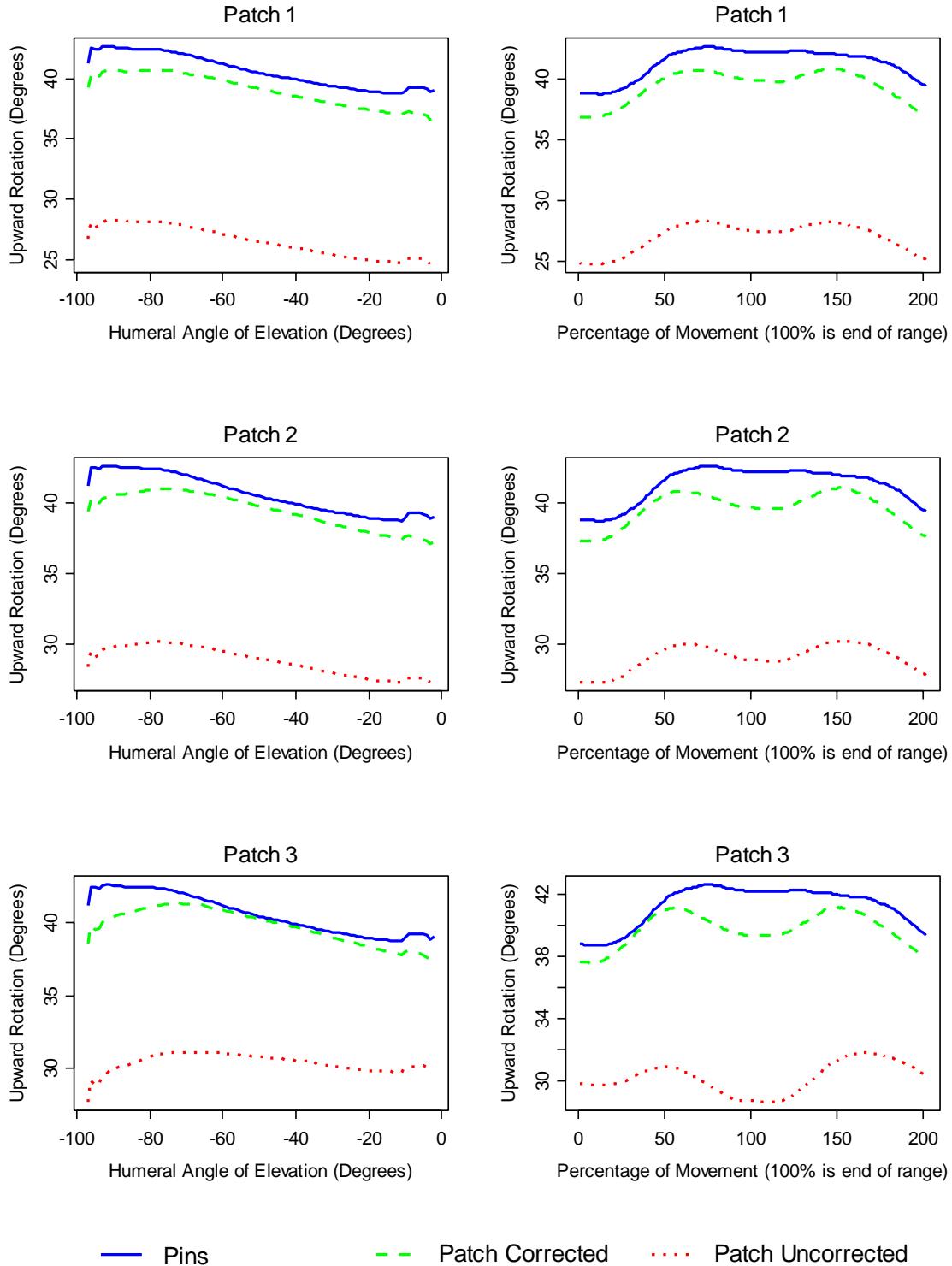
# Horizontal Adduction: Pins vs. Patches Subject3

## Upward Rotation



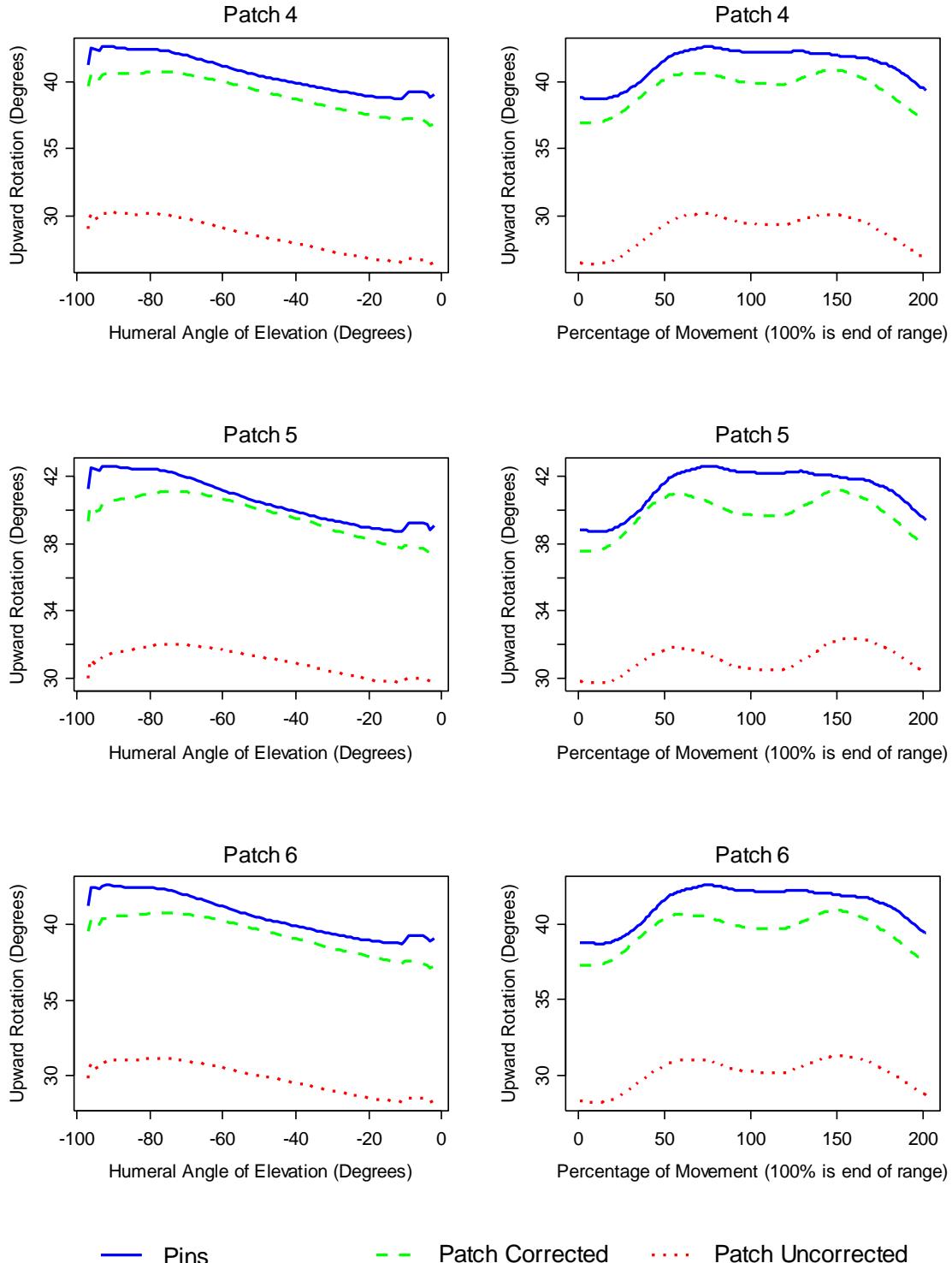
# Horizontal Adduction: Pins vs. Patches Subject4

## Upward Rotation



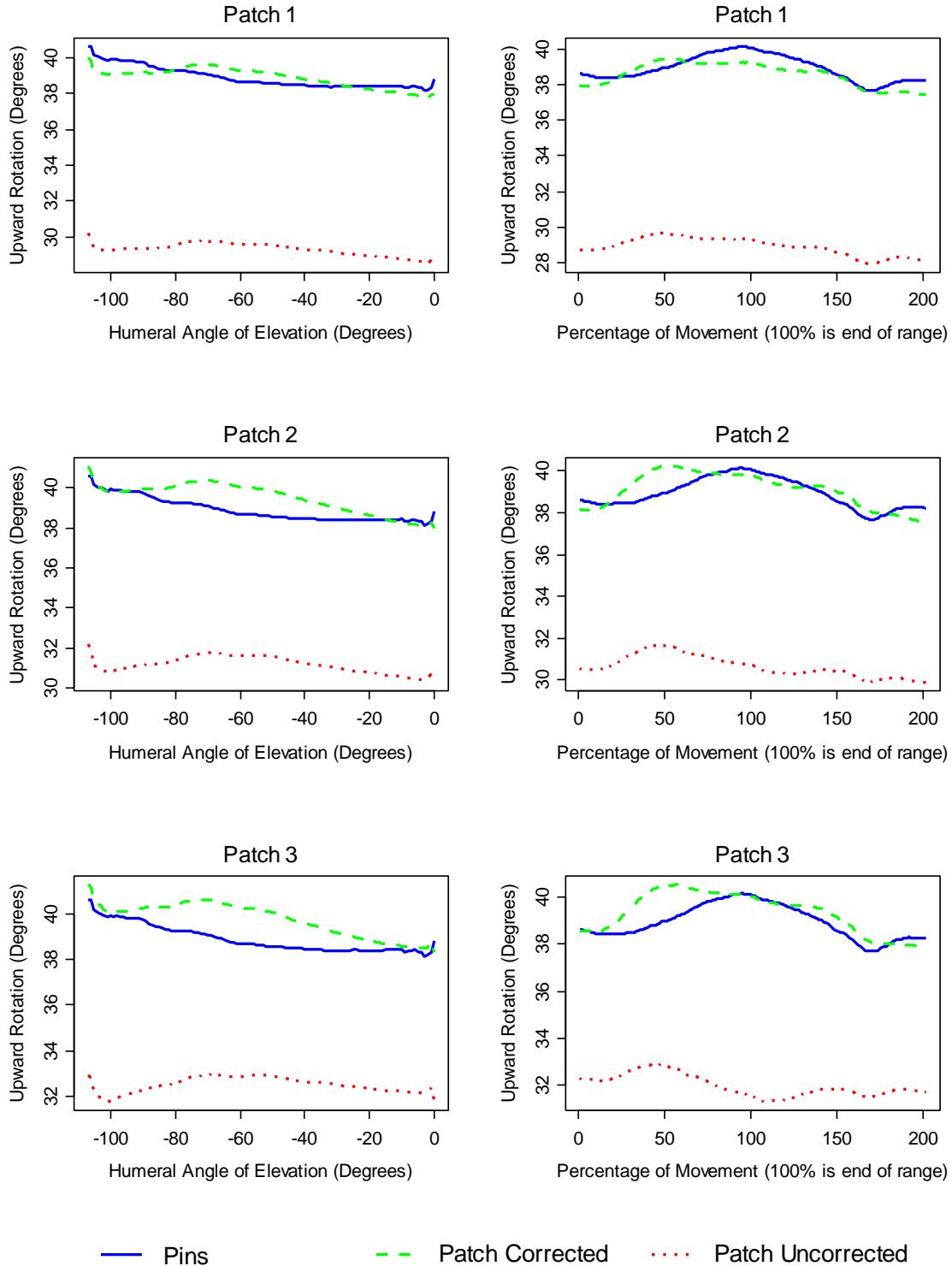
# Horizontal Adduction: Pins vs. Patches Subject4

## Upward Rotation



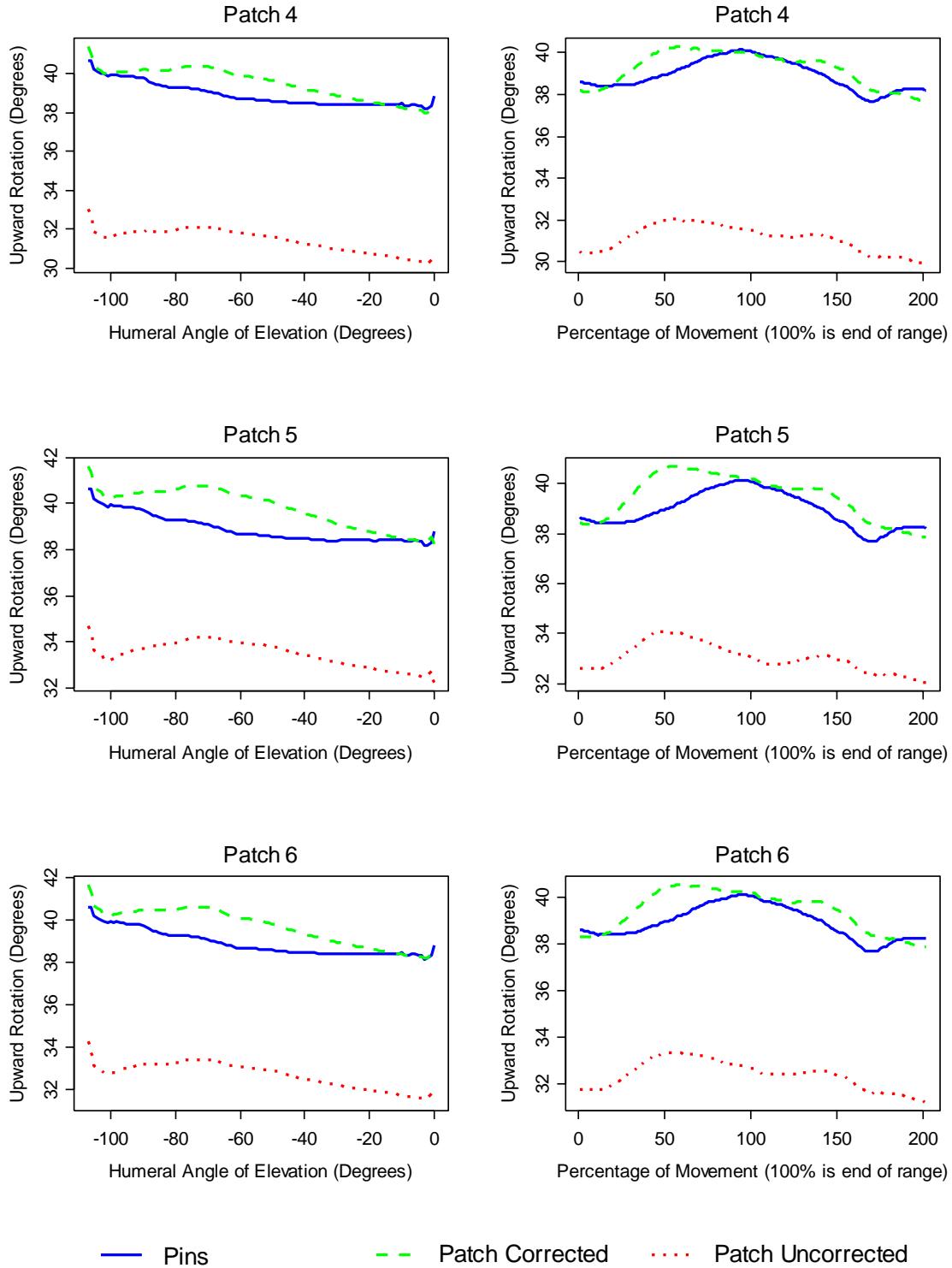
# Horizontal Adduction: Pins vs. Patches Subject5

## Upward Rotation



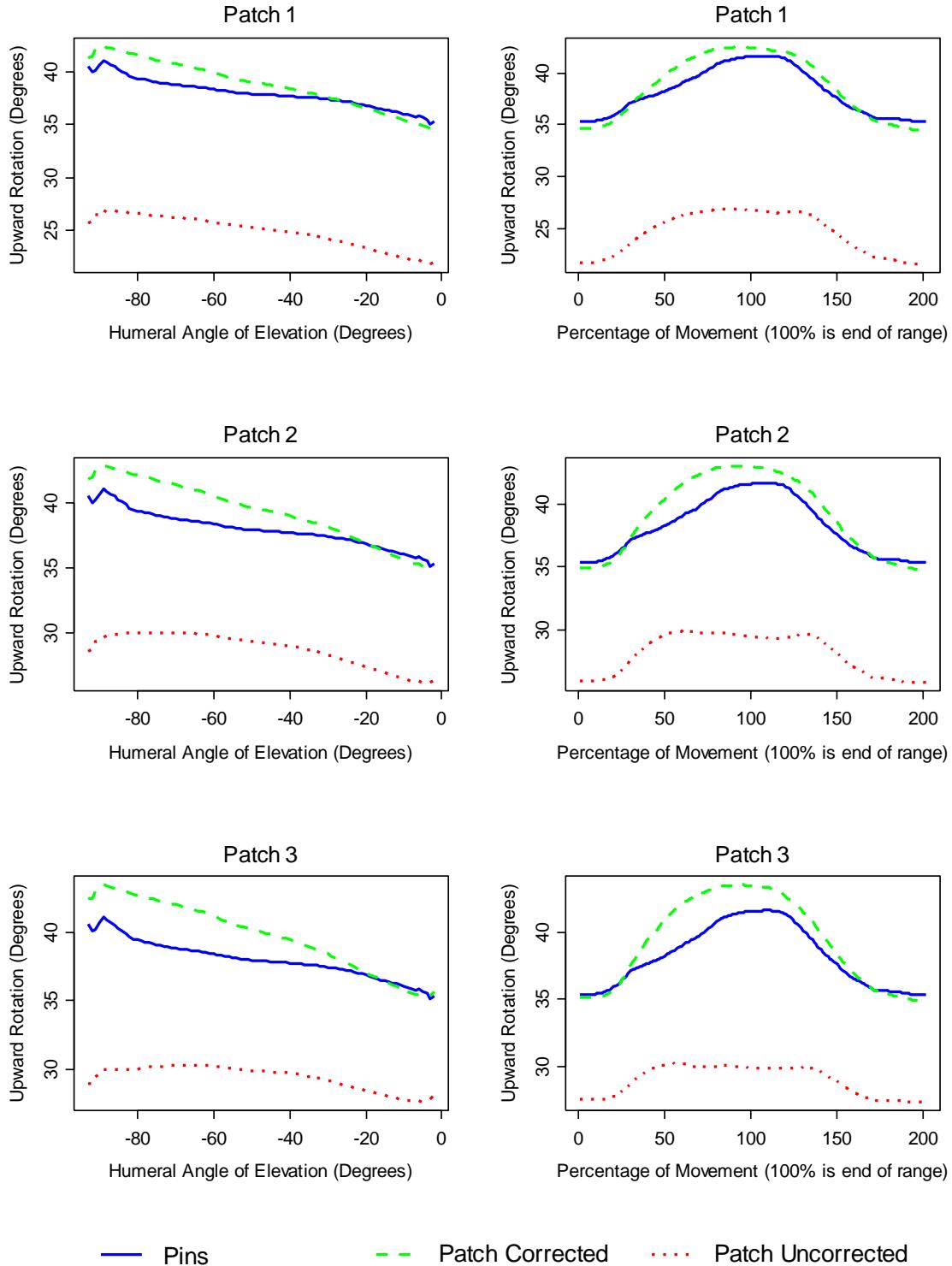
# Horizontal Adduction: Pins vs. Patches Subject5

## Upward Rotation



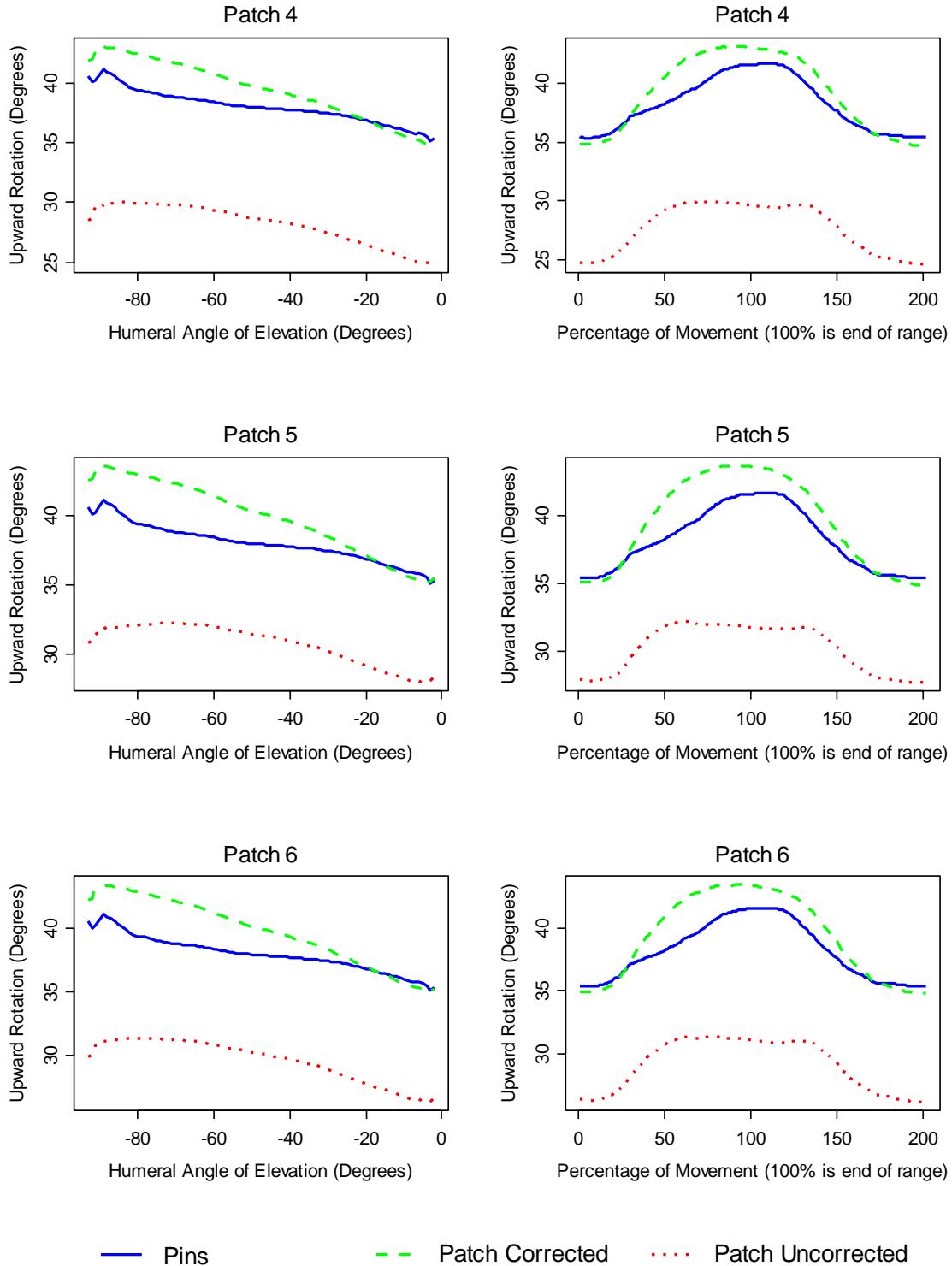
# Horizontal Adduction: Pins vs. Patches Subject6

## Upward Rotation



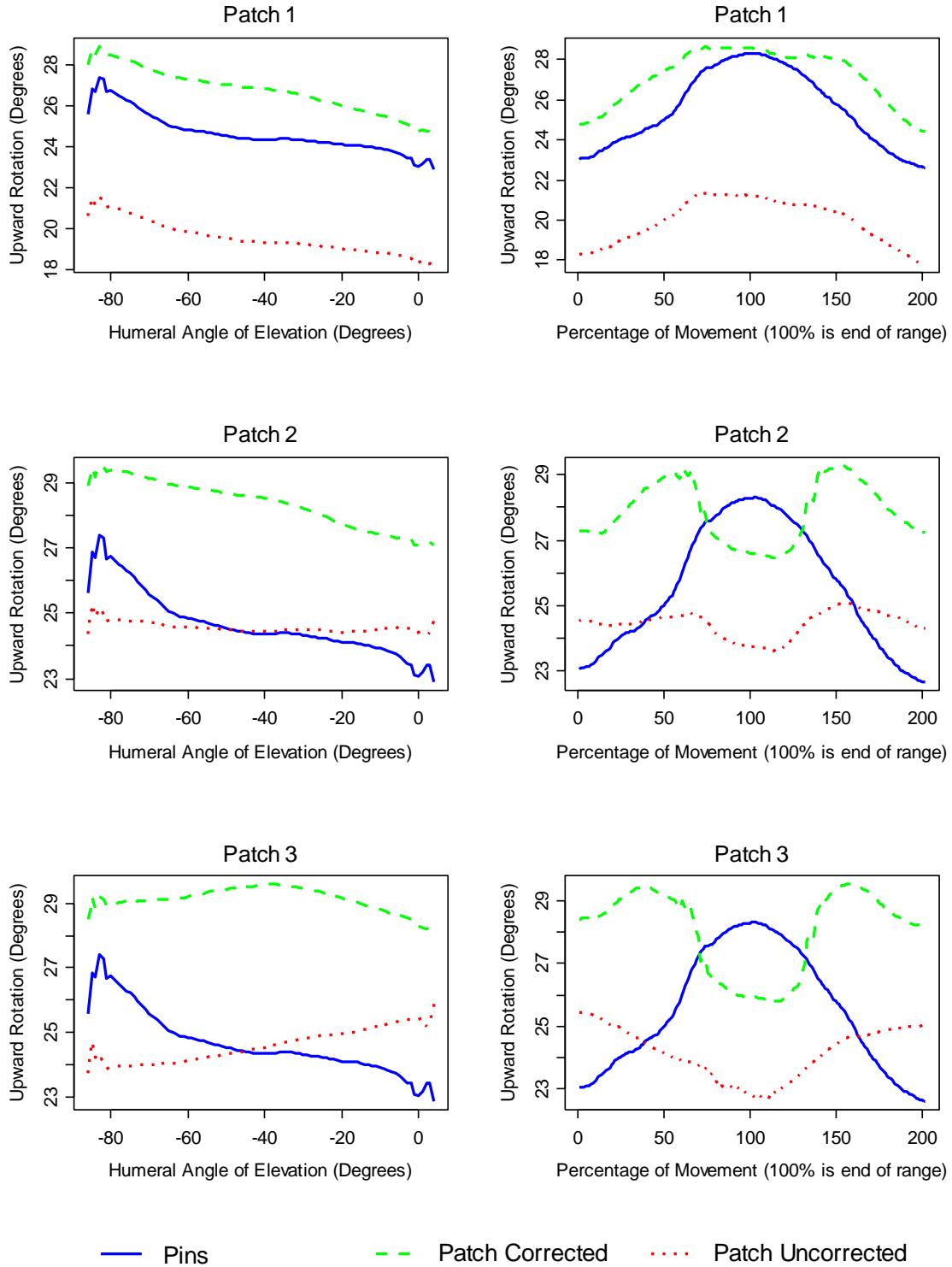
# Horizontal Adduction: Pins vs. Patches Subject6

## Upward Rotation



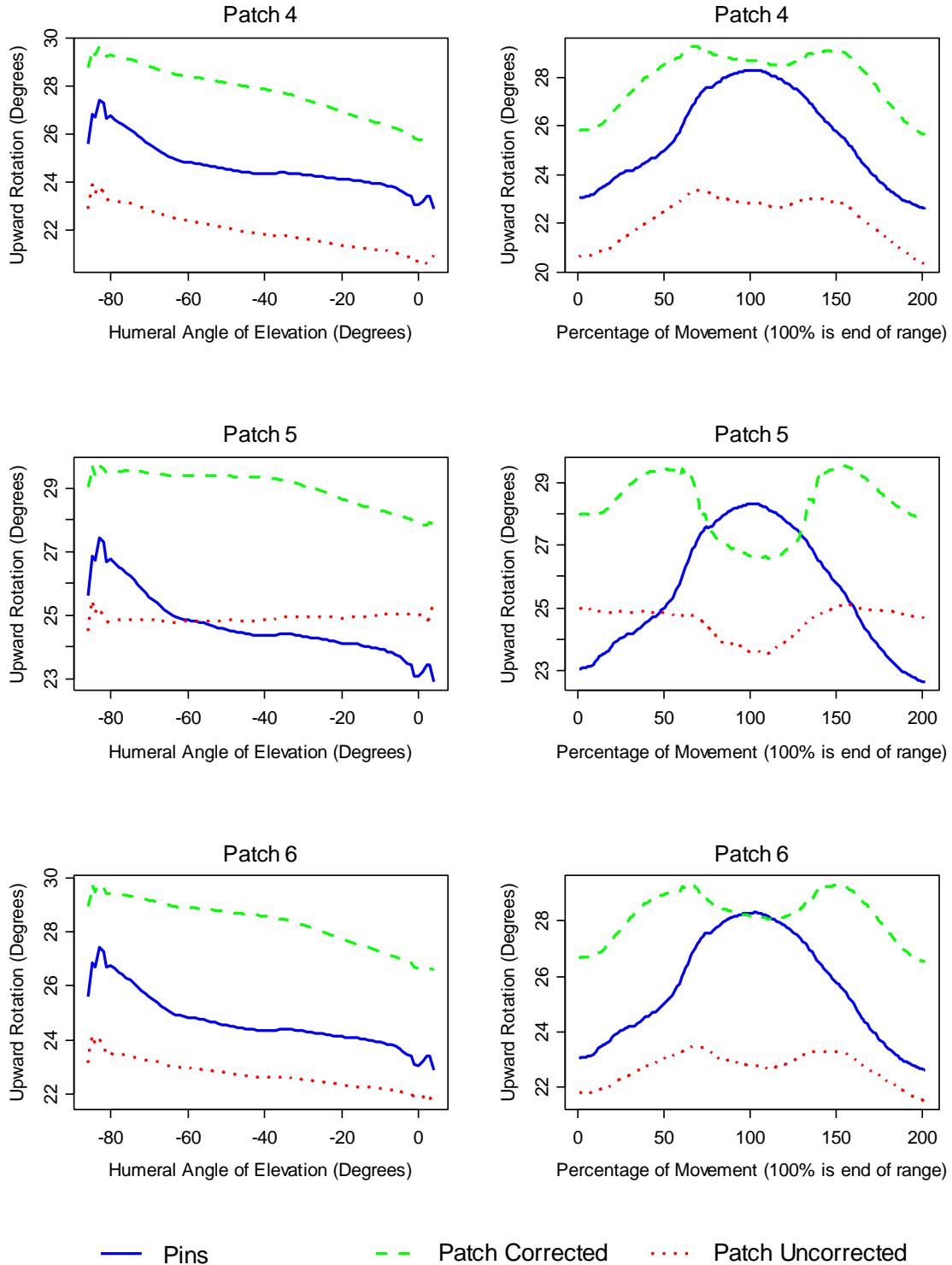
# Horizontal Adduction: Pins vs. Patches Subject7

## Upward Rotation



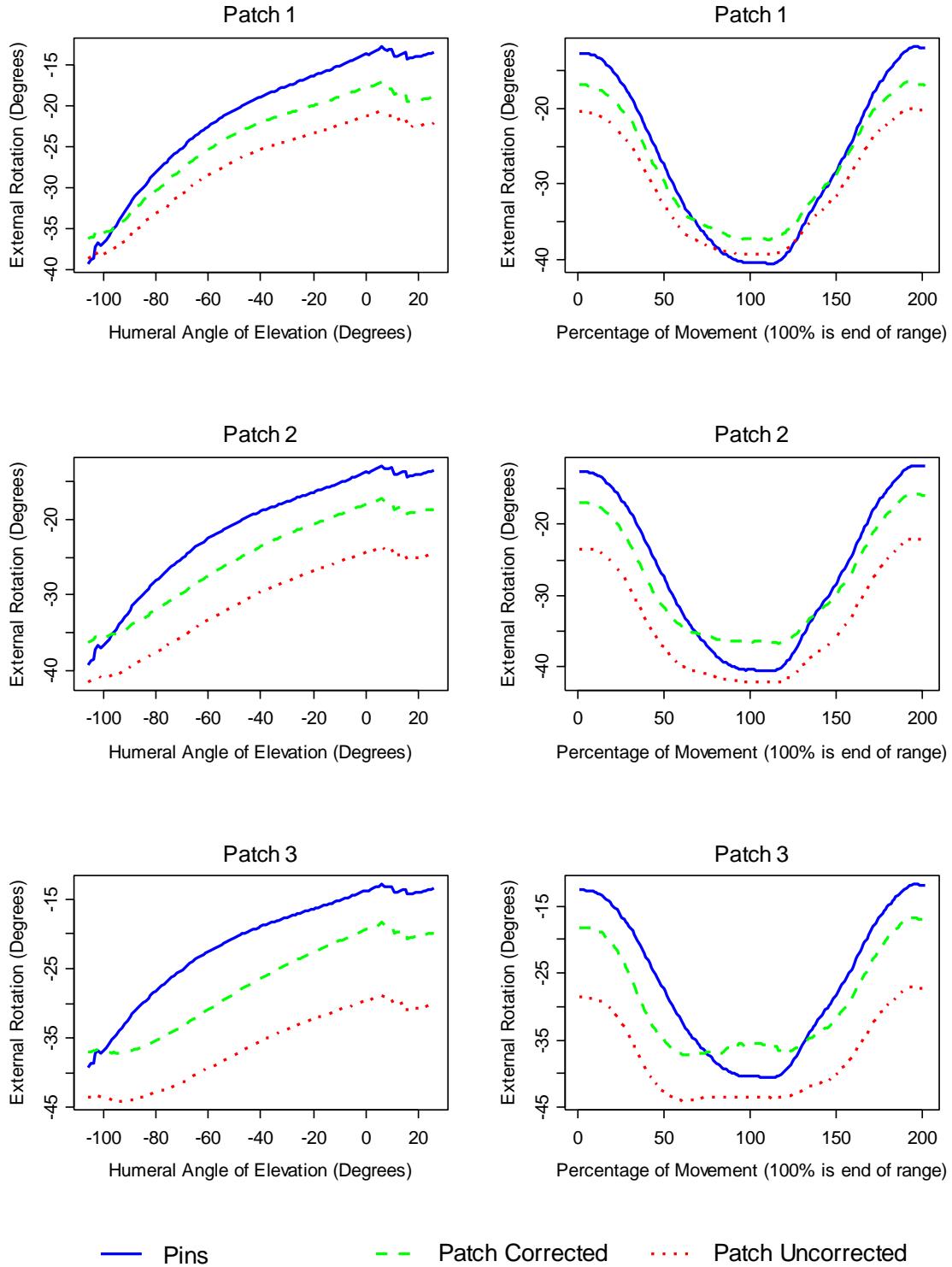
# Horizontal Adduction: Pins vs. Patches Subject7

## Upward Rotation



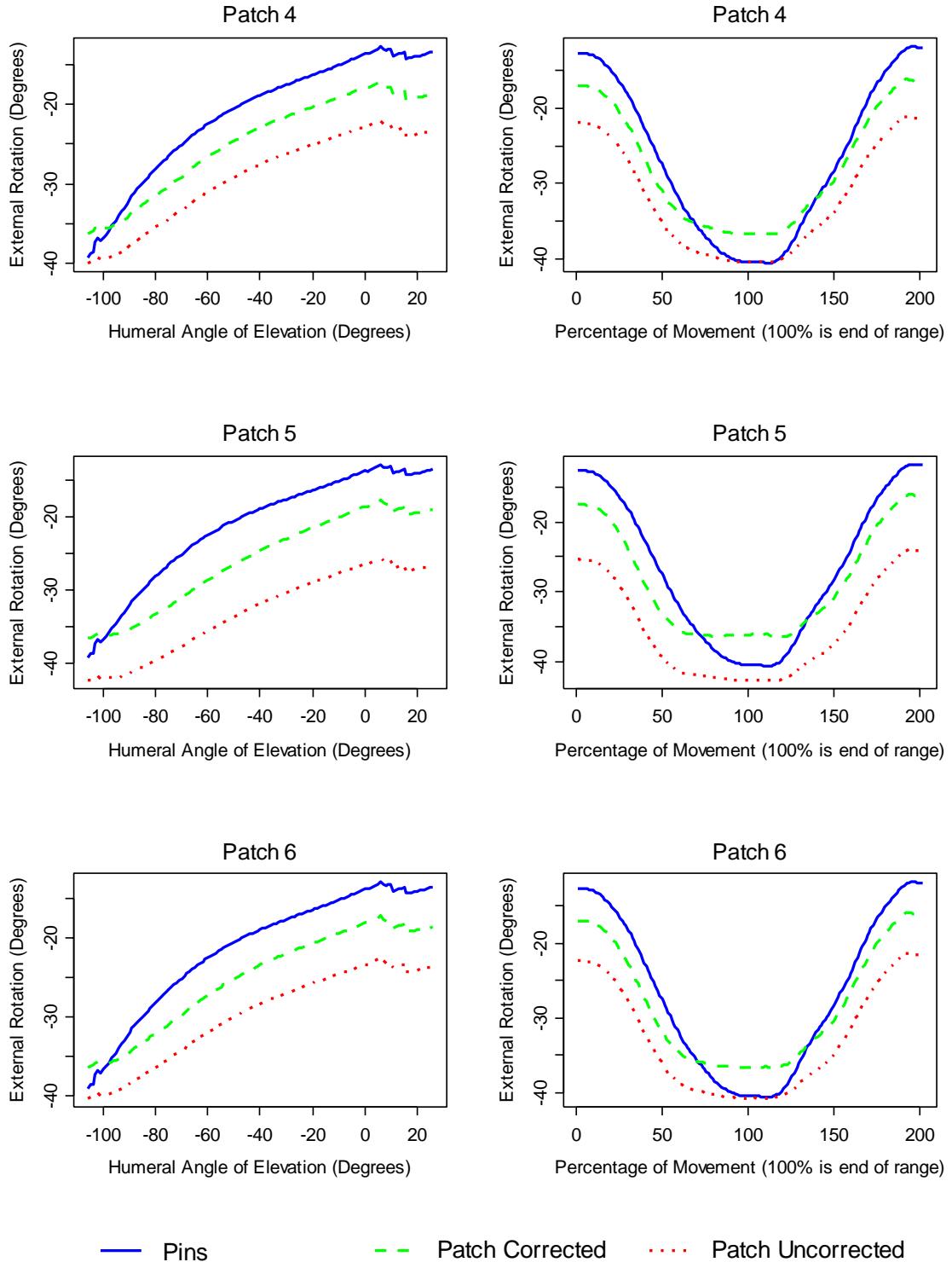
# Horizontal Adduction: Pins vs. Patches Subject1

## External Rotation



# Horizontal Adduction: Pins vs. Patches Subject1

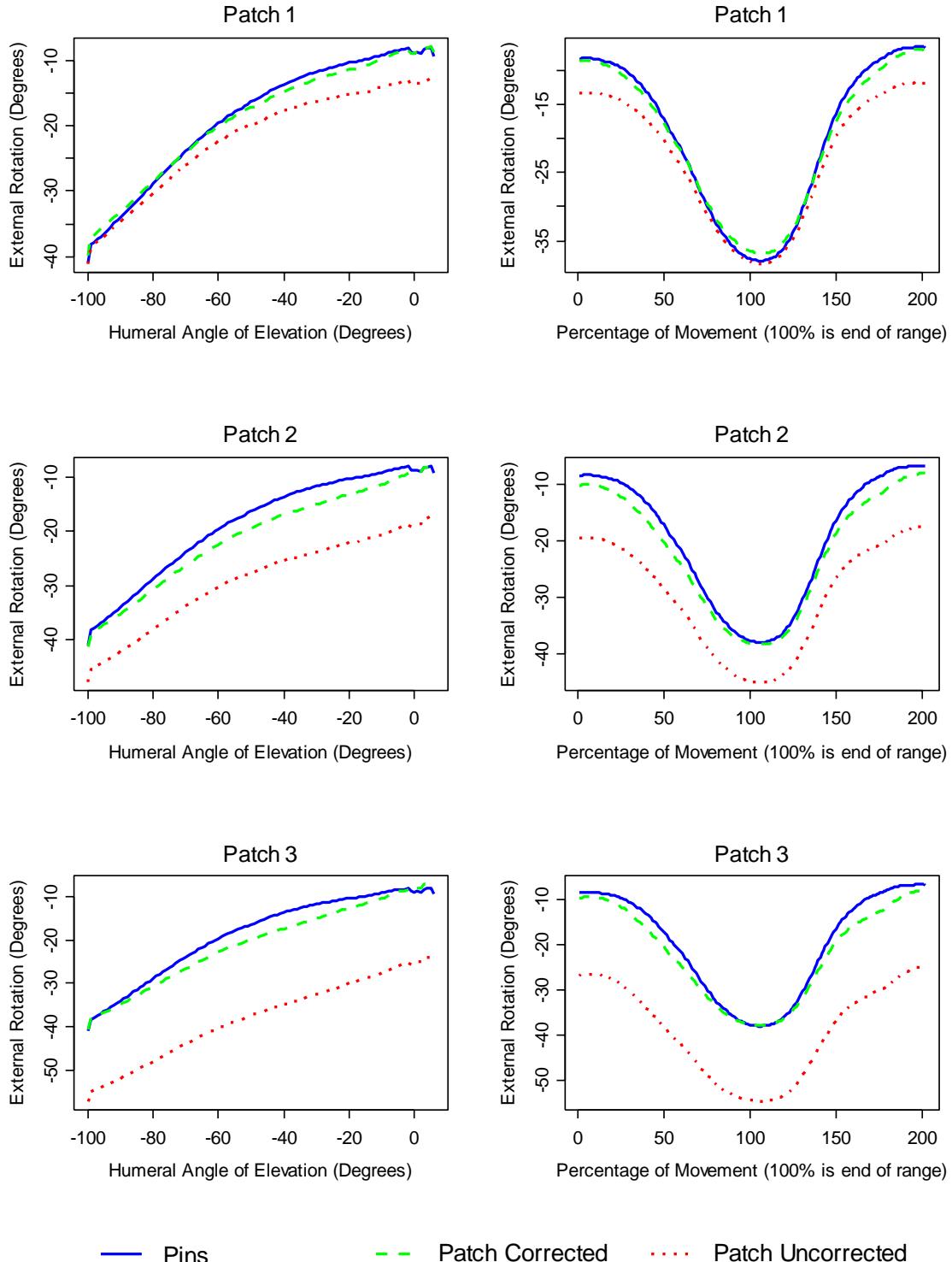
## External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

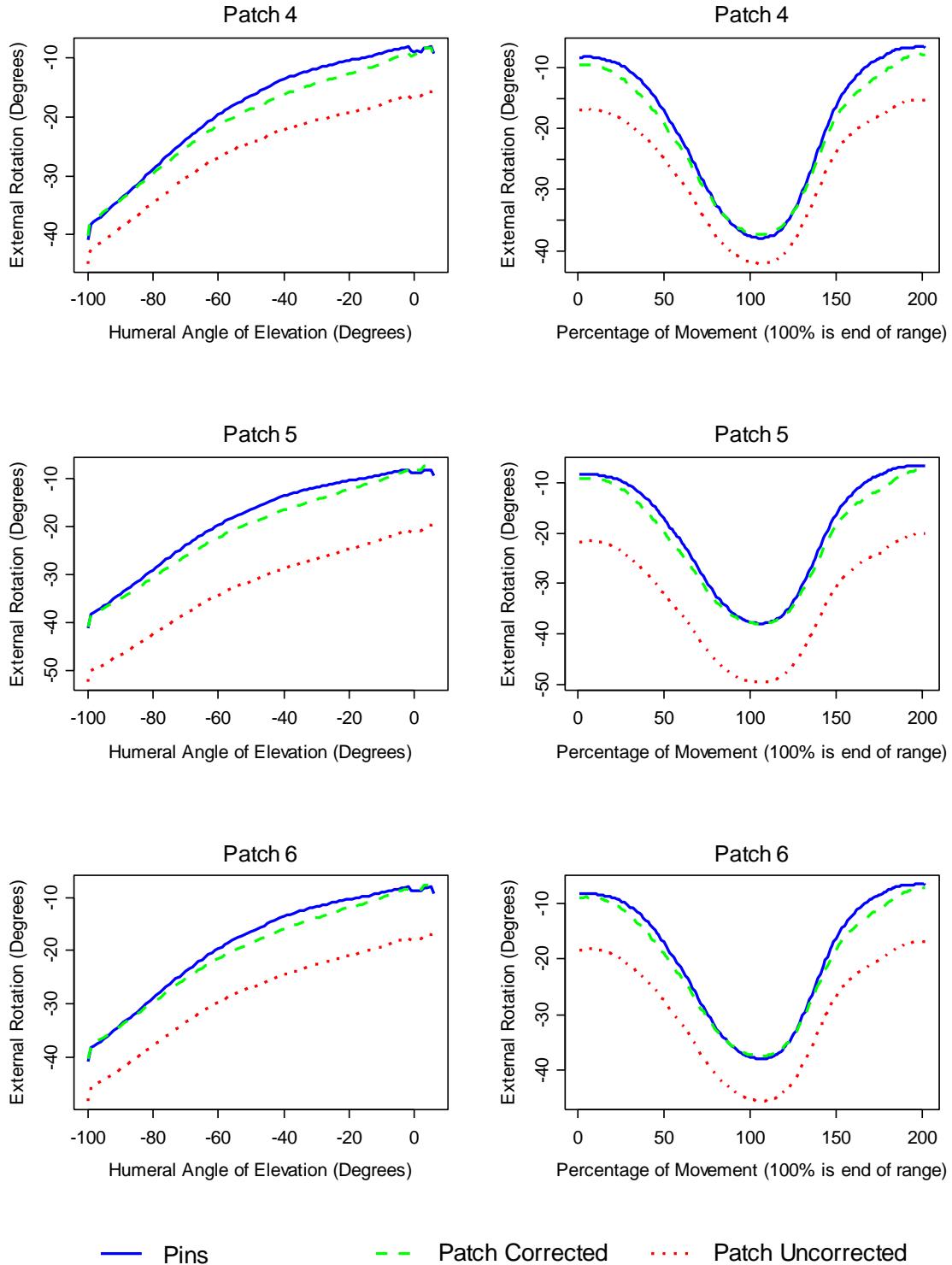
## Horizontal Adduction: Pins vs. Patches Subject2

### External Rotation



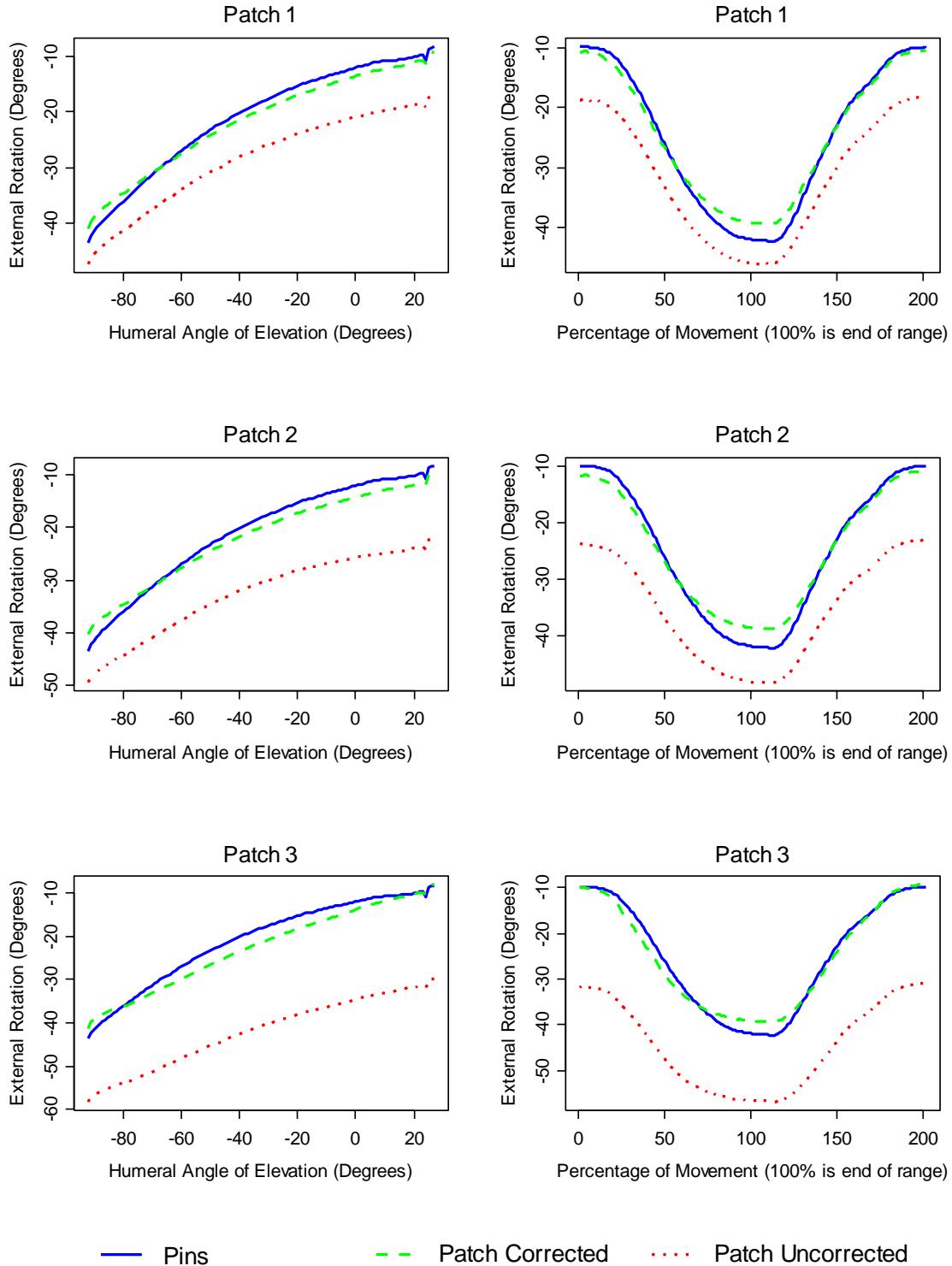
## Horizontal Adduction: Pins vs. Patches Subject2

### External Rotation



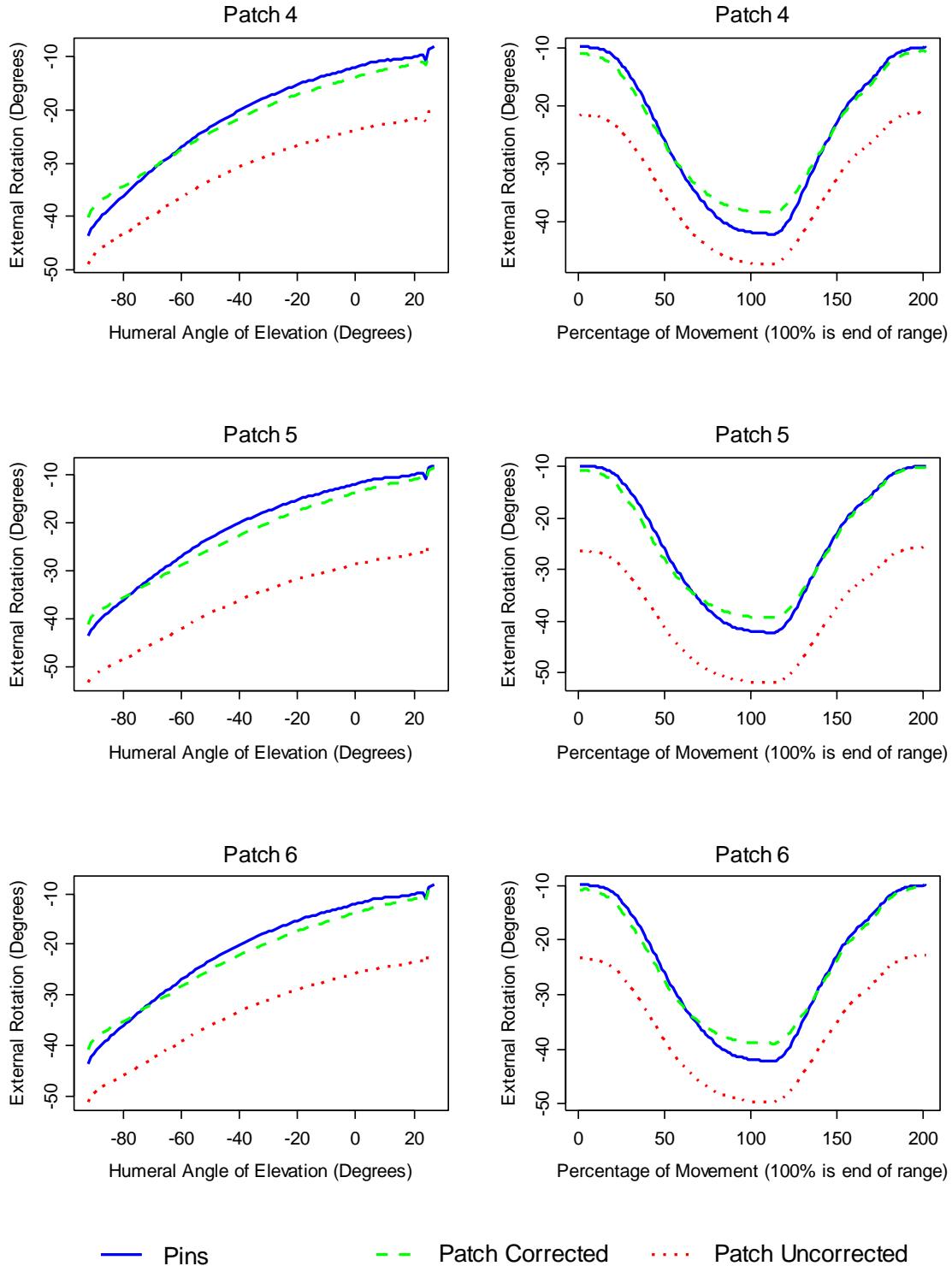
# Horizontal Adduction: Pins vs. Patches Subject3

## External Rotation



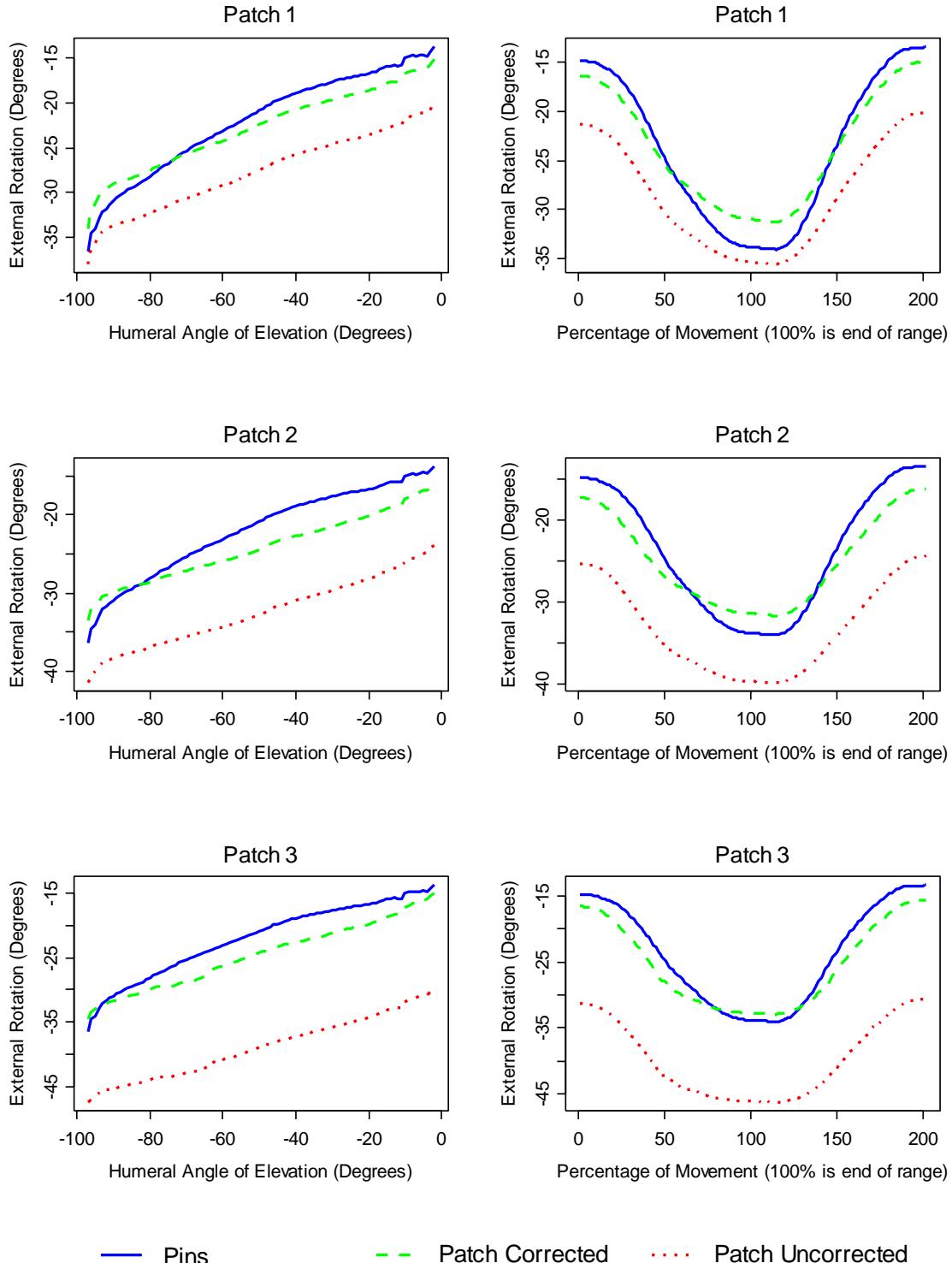
# Horizontal Adduction: Pins vs. Patches Subject3

## External Rotation



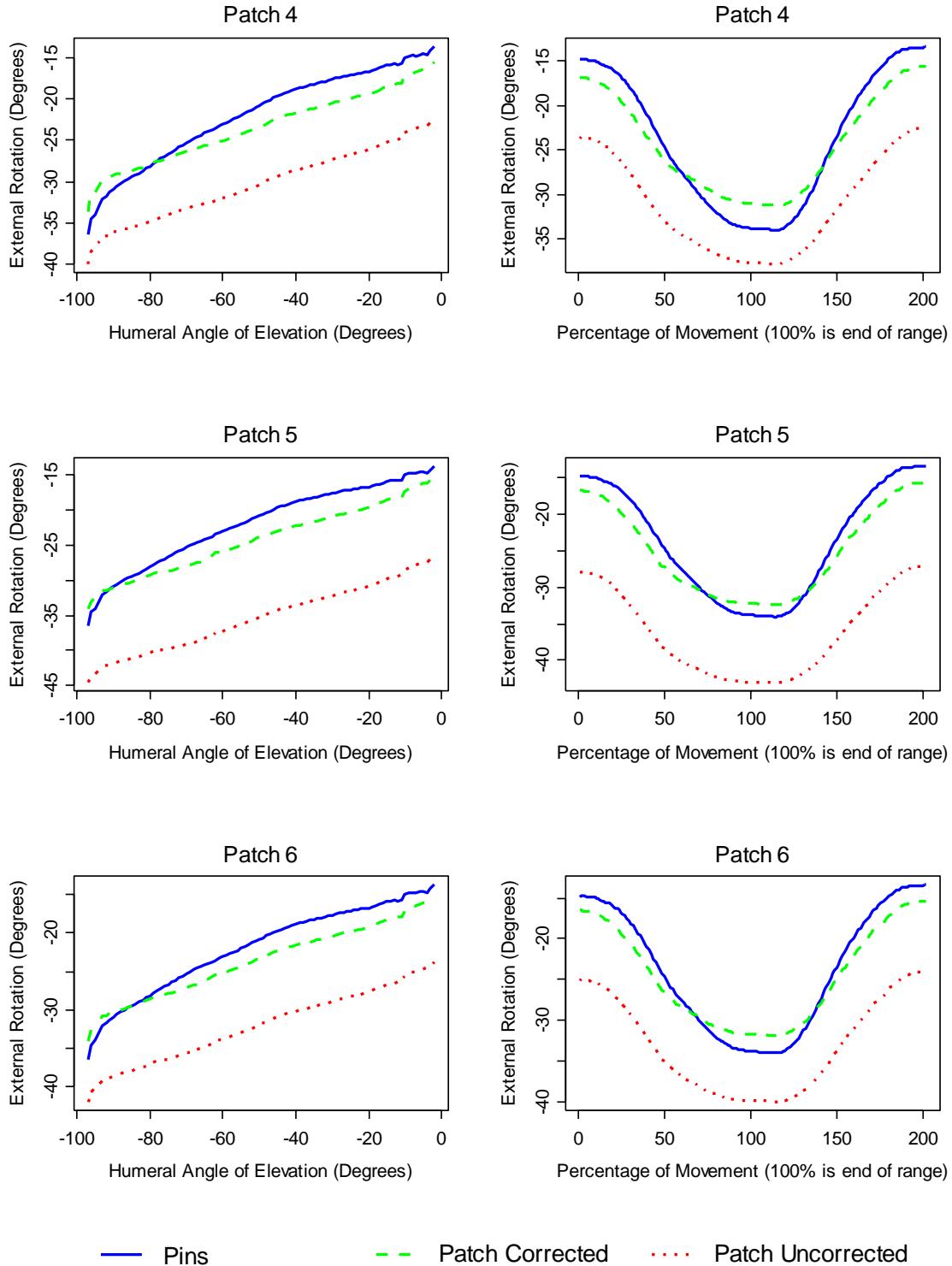
# Horizontal Adduction: Pins vs. Patches Subject4

## External Rotation



# Horizontal Adduction: Pins vs. Patches Subject4

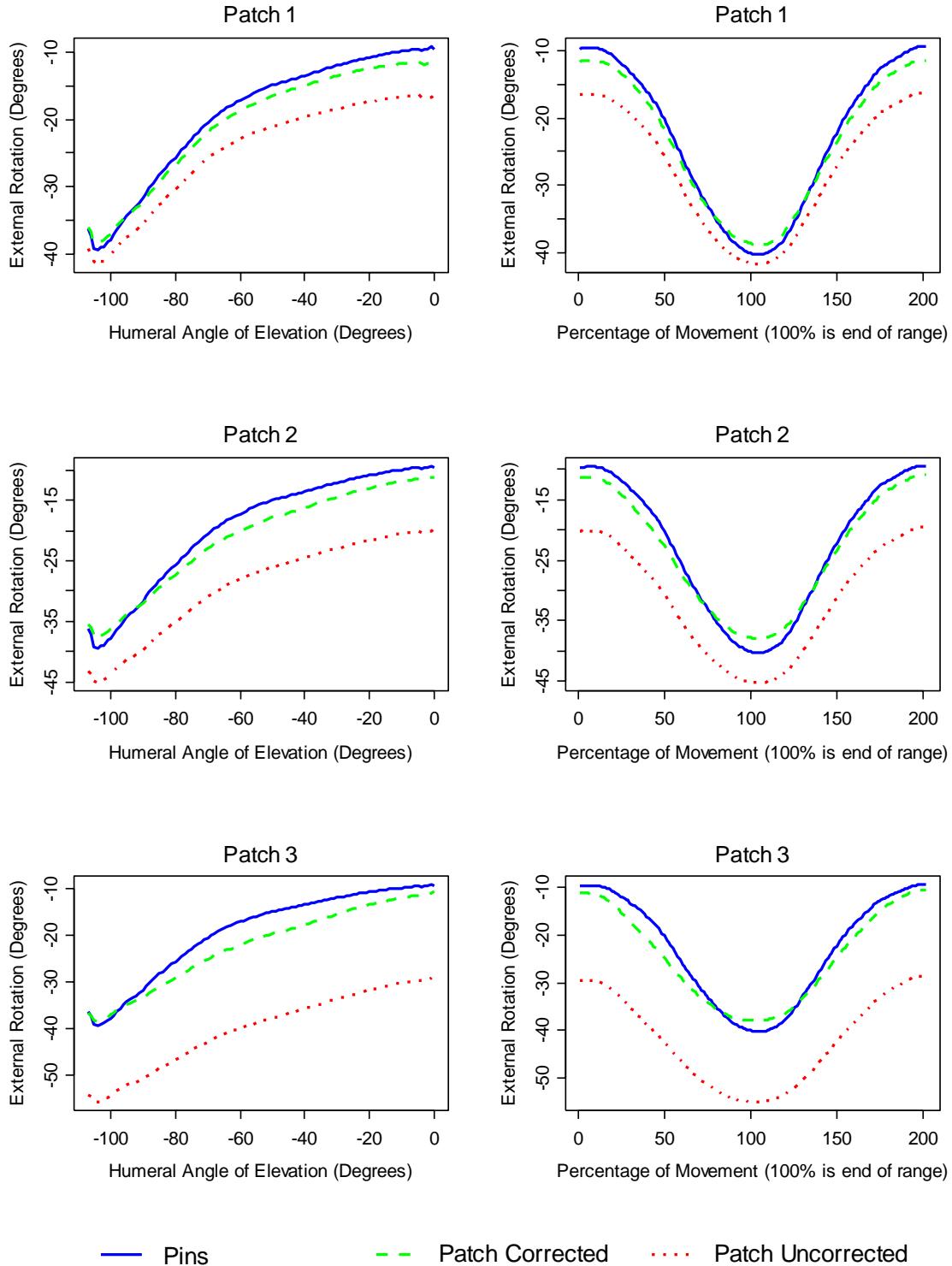
## External Rotation



— Pins      - - - Patch Corrected      ... Patch Uncorrected

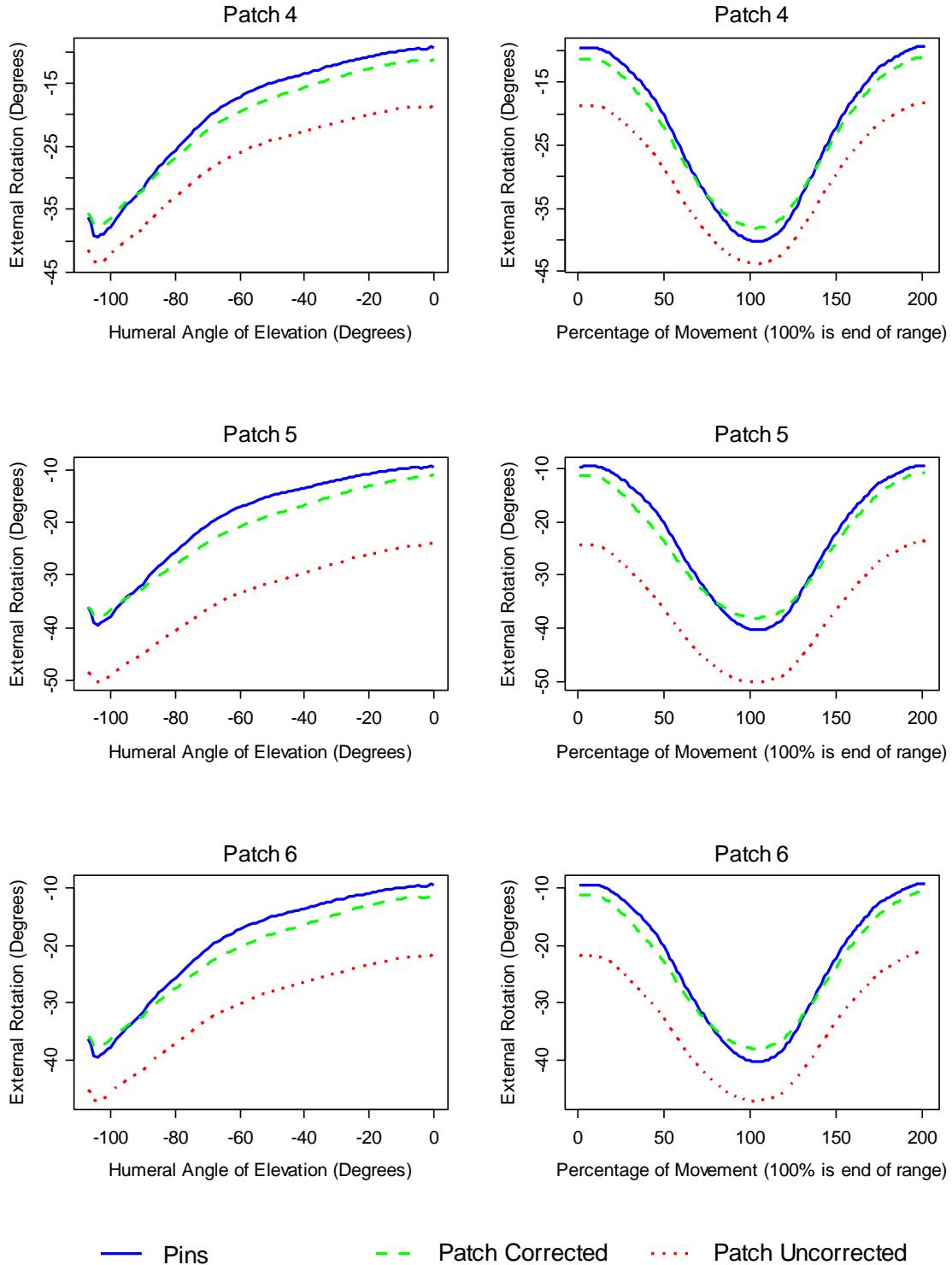
# Horizontal Adduction: Pins vs. Patches Subject5

## External Rotation



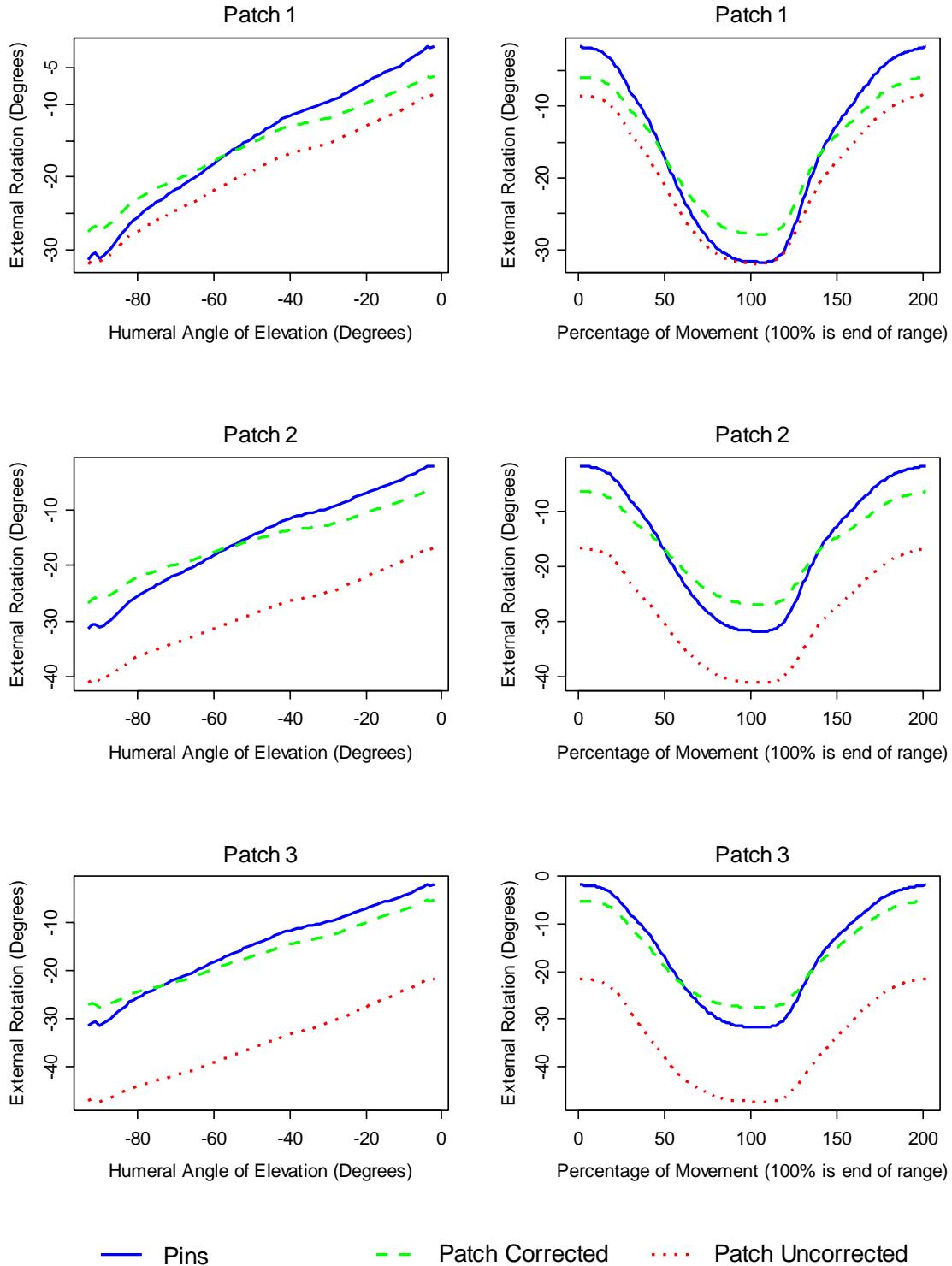
# Horizontal Adduction: Pins vs. Patches Subject5

## External Rotation



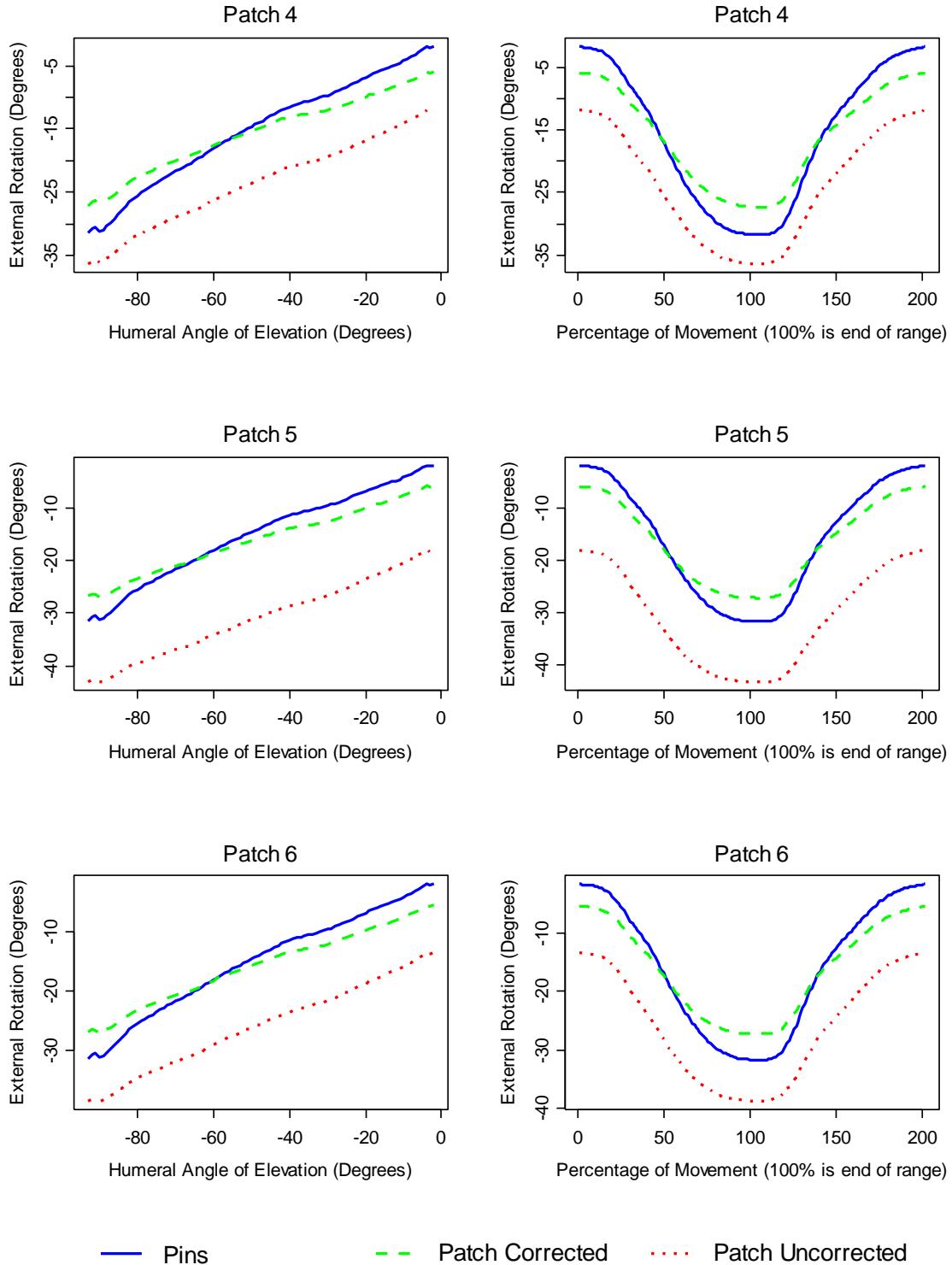
# Horizontal Adduction: Pins vs. Patches Subject6

## External Rotation



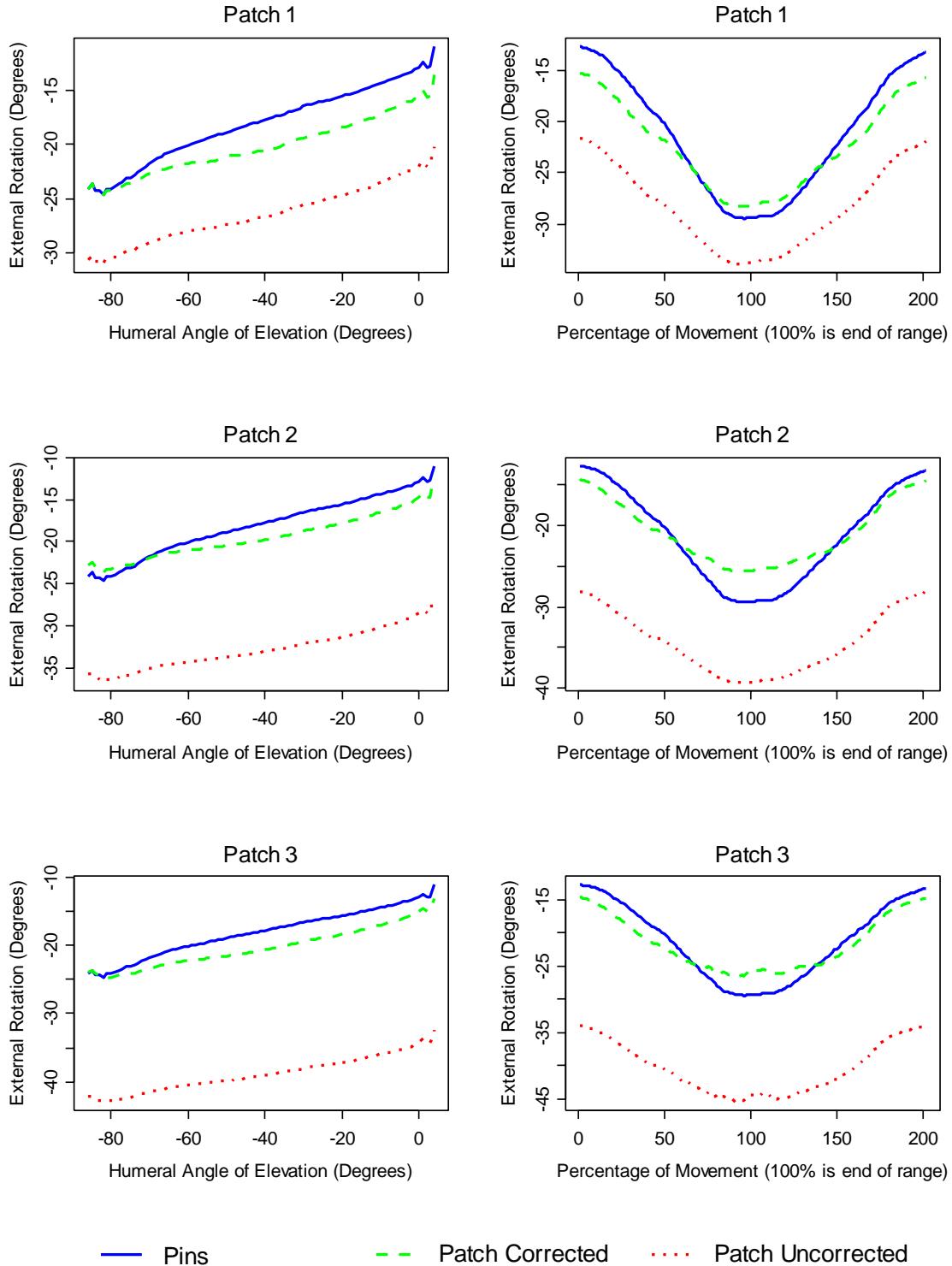
## Horizontal Adduction: Pins vs. Patches Subject6

### External Rotation



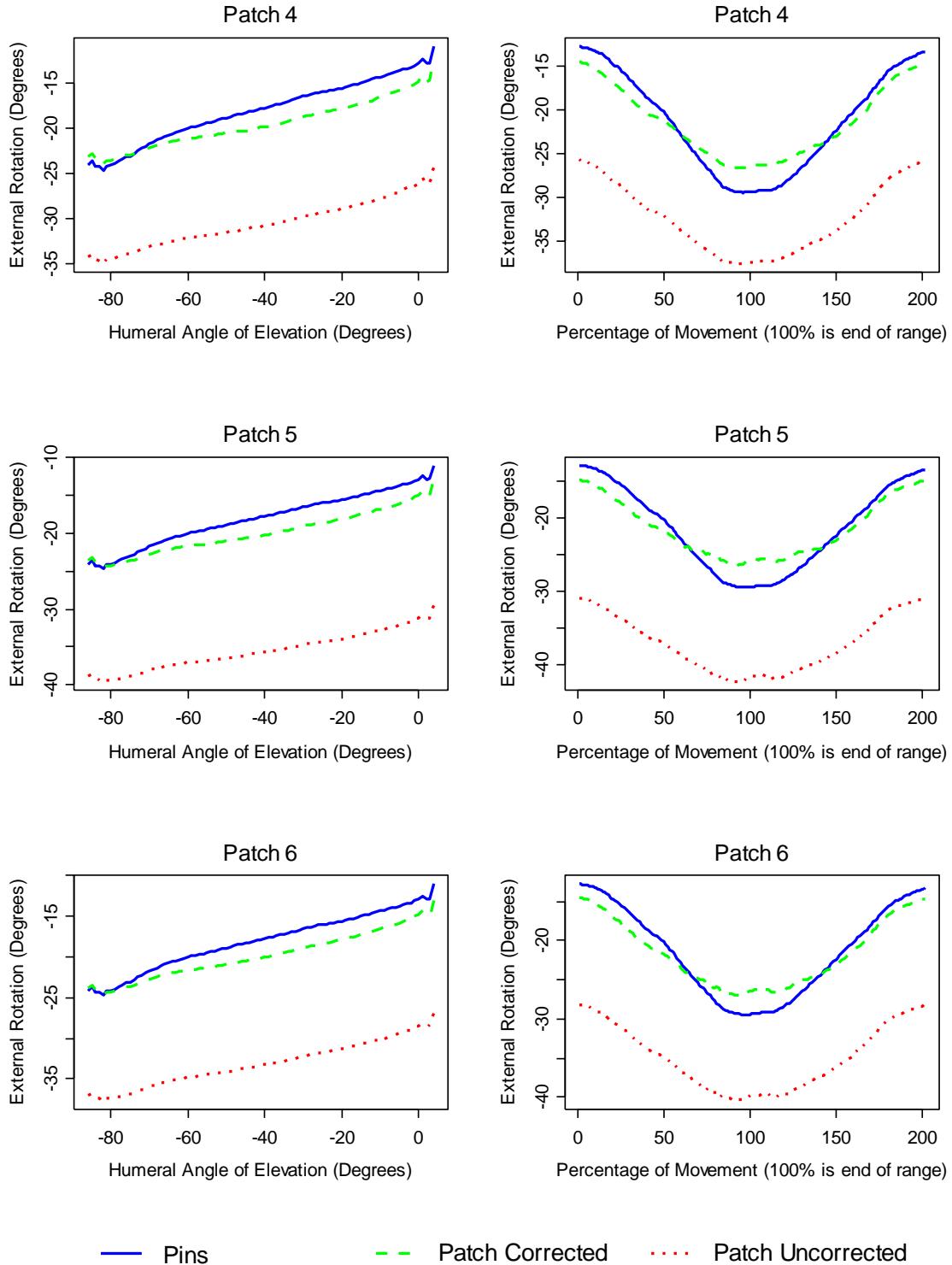
# Horizontal Adduction: Pins vs. Patches Subject7

## External Rotation



# Horizontal Adduction: Pins vs. Patches Subject7

## External Rotation



## Appendix F Shoulder Anatomy

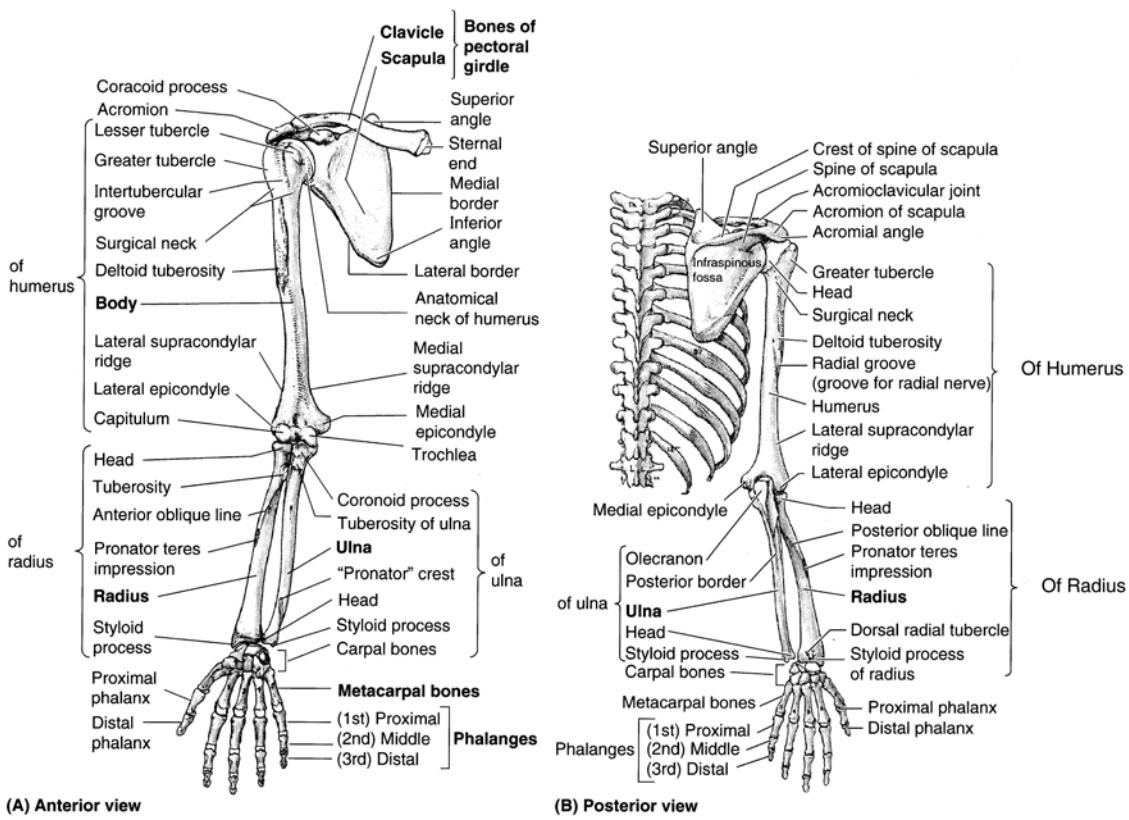


Figure F-1 Shoulder Anatomy modified from Moore and Dalley (Moore and Dalley, 1999).