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The effect of viewing angle on wrist posture estimation from photographic images using novice raters

Michael H. Lau*, Thomas J. Armstrong

University of Michigan, Industrial and Operations Engineering, 1205 Beal Ave, Ann Arbor, MI 48109, USA

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ABSTRACT

Observational assessment of wrist posture using photographic methods is theoretically affected by camera view angle. A study was conducted to investigate whether wrist flexion/extension and radial/ulnar deviation postures were estimated differently by raters depending on the viewing angle and compared to predictions using a quantitative 2D model of parallax. Novice raters ($n = 26$) estimated joint angles from images of wrist postures photographed from ten different viewing angles. Results indicated that *ideal* views, orthogonal to the plane of motion, produced more accurate estimates of posture compared to non-ideal views. The neutral (0°) posture was estimated the most accurately even at different viewing angles. Raters were more accurate than model predictions. Findings demonstrate a need for more systematic methods for collecting and analyzing photographic data for observational studies of posture. Renewed caution in interpreting existing studies of wrist posture where viewing angle was not controlled is advised.

1. Introduction

Observational methods are widely used by researchers and practitioners for ergonomic analysis of body postures. These methods provide valuable insight into understanding the causes of musculoskeletal disorders. The evaluation of worker posture by observational methods however, is believed to be prone to error from several sources.

Wrist posture has been recognized as a risk factor for work-related musculoskeletal disorders by the National Research Council (1999). Evidence indicates that awkward wrist posture *combined* with high hand forces or repetition is a risk factor for wrist disorders (Bernard, 1997), but the role of awkward posture alone is not as well understood. Improving the accuracy of assessment methods may help to clarify these relationships.

Generally, researchers estimate working postures directly or from recordings and assign ratings from them where more extreme postures are associated with higher risk. Existing observational methods differ in many aspects, including the types of posture analyzed and the metrics used to scale the postures. Examples of these methods include those interested in whole body postures (Corlett et al., 1979; Hignett and McAtamney, 2000; Karhu et al., 1977), those concerning the general upper limb (David et al., 2008; McAtamney and Corlett, 1993; Moore and Garg, 1995), and those examining wrist posture in detail (Armstrong et al., 1982; Colombini, 1998; Yen and Radwin, 2002). These methods are often used in lieu of methods for objectively measuring posture in occupational settings.

A review of postural assessment methods by Li and Buckle (1999) described a general lack of precision and reliability. Assessment and classification of postures of larger body segments had higher reliability than smaller joints (Baluyut et al., 1995; Bao et al., 2009; Jensen et al., 2000). Low inter-analyst agreement and significant misclassification of wrist posture were observed by several researchers (Bao et al., 2007; Lowe, 2004). Observers exhibited moderate validity compared to experts in assessing wrist posture, but faired poorly when compared to wrist goniometry data (Ketola et al., 2001). Despite these weaknesses being identified, what specifically caused the error in postural classifications had neither been identified nor reported (Genaidy et al., 1994). Bao et al. (2009) suggested that reliability depended on variability of the posture parameters, camera positions, video quality, and complicated work postures.

1.1. Parallax

Parallax is thought to be an important error source in posture analysis (Dartt et al., 2009; Stetson et al., 1991). Parallax errors

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* Corresponding author. Tel.: +1 734 936 0149; fax: +1 734 764 3451.
E-mail addresses: laumh@umich.edu (M.H. Lau), tja@umich.edu (T.J. Armstrong).

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Fig. 1. Single wrist flexion posture from four different viewing angles.

result when the viewing angle is not aligned with the axis of joint rotation (Paul and Douwes, 1993). Parallax affects how objects appear to us. In this case, the wrist appears differently depending upon at which angle it is viewed at (Fig. 1).

Parallax is a well-studied phenomenon with origins in astronomy. In the book *De revolutionibus orbium coelestium* (Copernicus, 1543), Copernicus stated that the earth's motion around the sun caused the retrograde and apparent motion of the planets, not the planets revolving around the earth. Planetary parallax is many orders larger than postural evaluation, but the systematic alteration of the appearance of objects caused by changes in perspective is highly relevant.

Parallax is almost always present when observing worker posture; workers move frequently and constantly change the view angle, often without the observer realizing it. Viewing angles are often not reported in posture studies (Juul-Kristensen et al., 2002; Mattila et al., 1993; McAtamney and Corlett, 1993; Spielholz et al., 2001; Stetson et al., 1991). Some researchers try to minimize any effect of parallax by observing workers from multiple angles (Baluyut et al., 1995; Juul-Kristensen et al., 2001; Lowe, 2004), sometimes simultaneously using video recordings (Yen and Radwin, 2000).

1.2. Parallax model

Paul and Douwes (1993) proposed a general model to quantify parallax introduced during photographic recording of posture. This model shows that as the angle between the line of sight and the axis of joint rotation increases in one direction, the observed joint angle appears to increase. As the view angle increases in an orthogonal direction, the observed joint angle appears to decrease.

The model can be applied to the analysis of wrist postures. For example, wrist angle (α) can be measured using a view with no parallax (Fig. 2a). When the angle between the line of sight and the axis of joint rotation increases (β), the dimensions of the hand (a' and c') are altered (Fig. 2b) and the apparent angle (α') is larger than the actual angle, ranging up to 180°. With an increase in the angle between the line of sight and the joint movement plane, the apparent angle decreases from the actual angle, down to a minimum of 0°.

This parallax model is based on two-dimensional line drawings and does not consider the effect of three-dimensional (3D) surfaces, shadows, etc. The wrist is not a simple stick figure and viewing images in 3D provides a richer experience, allowing one to integrate other visual cues. These visual cues, notwithstanding those from external objects, may include relative lengths of wrist segments, visibility of wrist creases, visible surfaces of fingertips, fingernails or sides of the hand, the prominence of finger tendons under the skin of the forearm, textural differences between the palm and back of the hand, depth cues (Nawrot and Joyce, 2006), light/shade, and contrast. When parallax exists, it is believed that observers are able to overcome its effects somewhat by using this added information.

1.3. View angle definitions

Here we identify three general categories of view angles that could be adopted by an observer of a particular joint posture. *Ideal*

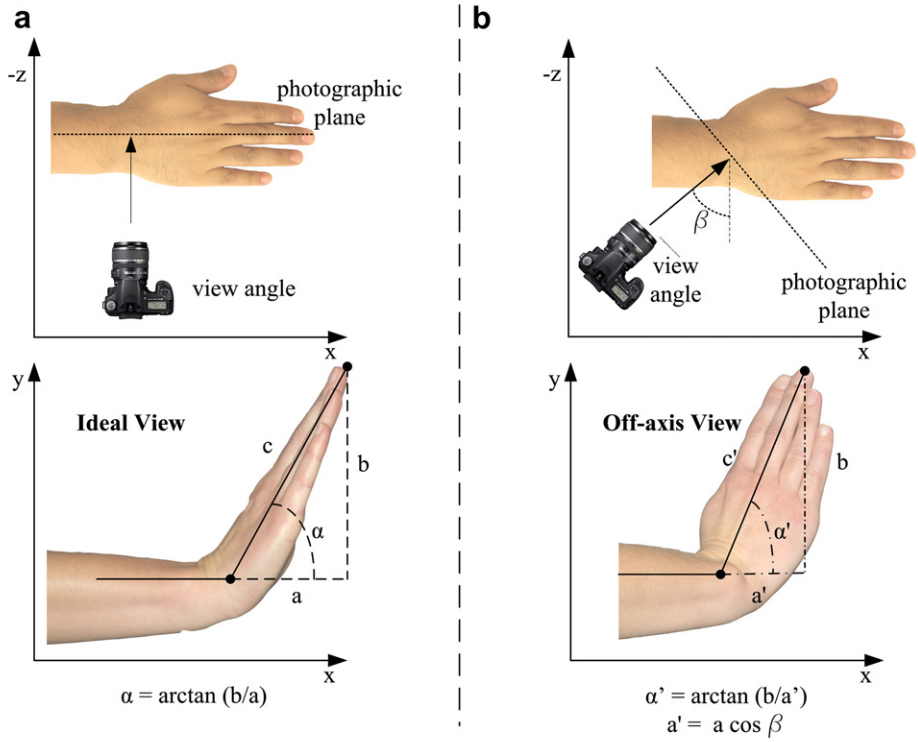

Fig. 2. 2D model depiction of the wrist segment as seen from two different views.

view angles produce no perspective distortion (i.e., no parallax) and presumably lead to the most accurate posture estimation. These ideal angles are defined here to be orthogonal to the plane of motion and in the axis of rotation. An *in-line view* is directly in the plane of joint motion and through the axis of rotation. It is believed to produce the largest distortion because the wrist appears as a straight line with no visible joint angle. An *off-axis view* is neither orthogonal to nor in-line with the plane of motion and causes the joint angle to appear larger or smaller than it actually is depending upon the view angle. The view angles selected for this study include ideal views, in-line views, and several off-axis views that might typically occur when observing or photographing a worker in person.

1.4. *Study objectives*

This study was conducted to investigate whether wrist flexion/extension and radial/ulnar deviation postures were estimated differently by subjects for different viewing angles. The null hypothesis was that there was no difference between observer and predicted parallax error between different viewing angles. We aimed to test this hypothesis and provide data about the accuracy and precision of posture estimates from different viewing angles.

The greatest effect of parallax was expected to be seen in the in-line views. From these views, the apparent wrist angles all appear as 90° or 0° because the joint angle is not visible. For off-axis views, the measured effect of parallax was expected to be more pronounced as the wrist angle increases or as the view angle moves away from the ideal view. These conditions were expected to produce a corresponding decrease in accuracy. Parallax was not expected to affect the ideal views.

2. Method

2.1. *Image preparation*

The right hand and wrist (hand length = 15.4 cm; breadth = 7.5 cm) of a 1st percentile Caucasian female research associate were photographed in sixteen postures from ten different view angles (Fig. 3). The view angles were labeled according to the surface of the neutral wrist that is captured by that view. The wrist was positioned in nine flexion and extension (F/E) (F90°, F60°, F45°, F30°, 0°, E30°, E45°, E60°, E90°) and eight radial and ulnar (R/U) deviation (R30°, R20°, R10, 0°, U10°, U20°, U30°, U45°) postures. Wrist postures were obtained by aligning landmarks drawn on the model's hand, wrist, and forearm to clear Plexiglas marked with the desired angles. The view angles were selected to represent a range of typical view angles. A single associate was used to create the experimental images to isolate the effects of parallax as much as possible.

2.2. *Equipment*

A digital SLR camera was used (Canon 6.0MP, focal length = 28 mm). Each image contained the hand, wrist, forearm, and sometimes part of the torso. The camera-to-wrist distance was set at 117 cm (46″), which optimized image size and kept hand size constant in the images. The internal flash was used and ambient fluorescent lighting was controlled. Shadows were minimized, but could not be completely eliminated. Background objects were concealed using a patterned backdrop. This backdrop was selected to provide visual stimuli in the absence of recognizable objects.

2.3. *Participants*

Twenty-six university students with normal/corrected vision participated and received monetary compensation. Participants had little to no prior experience in ergonomic posture analysis.

2.4. *Protocol*

Participants were given a short training session. Simple diagrams of a wrist positioned in flexion, extension, and ulnar and radial deviation with lines drawn on the long axes of the forearm and hand were shown to the participants. The angle to be rated was indicated to them for each posture. Eight practice trials were given using exemplar images captured from ideal views and feedback was given after each trial. Participants verbally indicated that they understood how to perform the task prior to the start of the experimental conditions. The diagrams were made available throughout the study as reference if the participant needed them. Participant use of these materials was not recorded, but appeared to be minimal. The study was conducted using an 18″ LCD monitor, where images were approximately one-half of the screen area.

Participants were instructed to estimate wrist posture in degrees for each presented image of wrist F/E or R/U deviation.

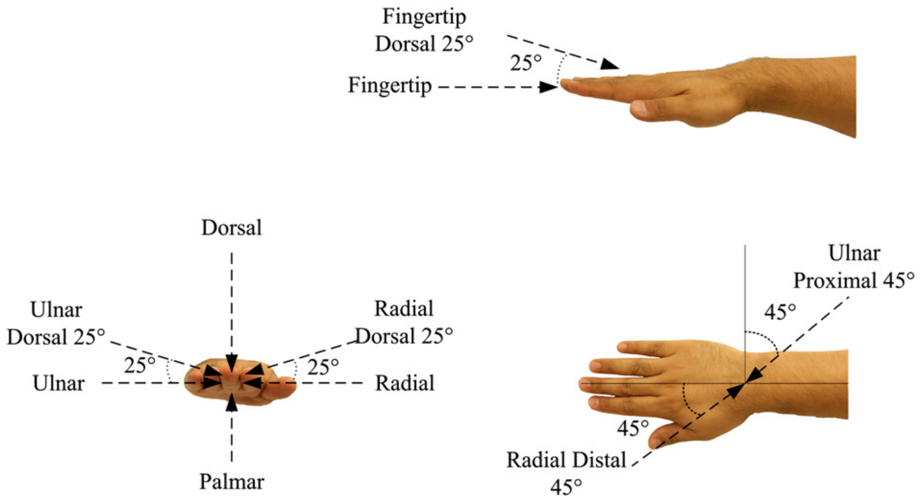

Fig. 3. Camera view angles labeled by surface of hand captured in image.

Participants were not informed of the specific study objectives and were not given information of the view angles, nor were they informed of the purpose of the study. Feedback was not given during the experiment.

Trials were blocked by movement type (flexion/deviation) to eliminate the need to distinguish between posture types. Wrist images were presented randomly using experimental software (MediaLab v2006.1.29). To prevent estimation beyond the expected range of motion as a trained expert would do, maximum limits were set for each posture type (F: 90°, E: 120°, U: 45°, R: 30°). A full factorial design was used. Each participant performed 170 different observations.

3. Results

Observations were performed for all conditions by all subjects. The results are presented separately by F/E and R/U deviation. Three values were used for comparison: *actual* wrist angles, *apparent* angles (model predictions), and corresponding *observed* angles (subjects' estimations). The difference between the observed and actual angles and the absolute value of the error was used to calculate the mean error for all conditions.

3.1. Flexion and extension

Actual, apparent, and observed wrist angles are shown for F/E postures in each chart in Figs. 4 and 5 grouped by ideal views (Fig. 4) and in-line and off-axis views (Fig. 5). Flexion postures are negative angles and extension, positive.

In the ideal views, the model outputs (apparent angles) are equal to the measured wrist angles. Subjects rated flexion postures more accurately than extension postures. The E90° posture was underestimated by subjects by mean values ranging between 6° and 30° across views.

The model predicts that all F/E angles seen from the in-line views (Fig. 5a) would appear the same: as 0° for and all F/E angles and 90° from the Fingertip and Fingertip Dorsal 25° views (Fig. 5b). The observed angles did not follow these predictions, but instead aligned more with the actual angles. Mean errors for these views ranged between 7° and 14° and were comparable to those observed in other views. Interestingly, observed values from the Radial Distal 45° and Ulnar Proximal 45° (Fig. 5c) views appeared to align more with the predicted values than with the actual angles. Observed values from the Radial Dorsal 25° and Ulnar Dorsal 25° views (Fig. 5d) were similar to each other and to the ideal views.

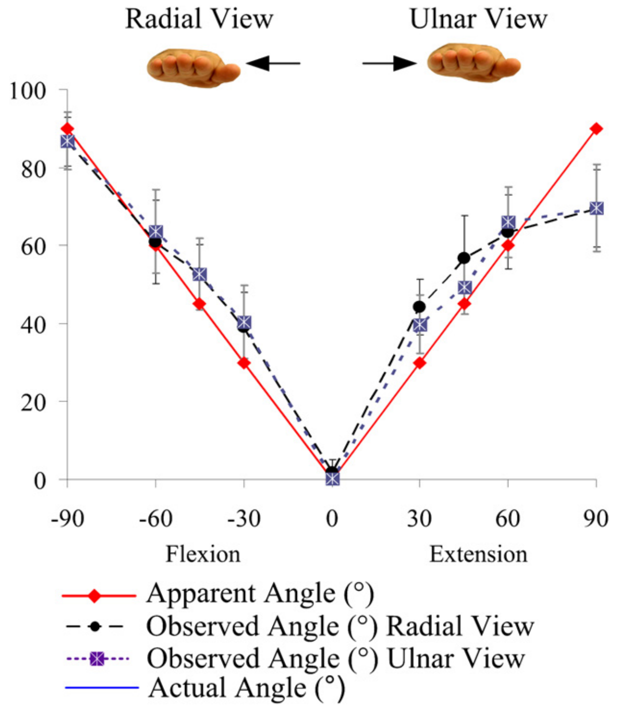

Fig. 4. Ideal views – actual, apparent and mean estimated angles (±1SD) are shown (in °) for F/E postures (actual angle = apparent angle).

3.2. Posture underestimation and overestimation

The estimates were evaluated for whether they were greater than, equal to, or less than the actual wrist angle. The proportion of overestimation, underestimation, and exact responses are shown separated by viewing angle in Table 1; the same is shown by posture in Table 2 along with the mean error. In total, 38% of the trials contained underestimates, 39% had overestimates, and 23% had no error. The range of mean error was largest for the Fingertip View (−25° to +26°) and least for the Radial View (−12° to 14°). The F90° posture was never overestimated because participants were instructed that 90° was the limit of the range of motion. The F60° and E90° postures were underestimated 68% and 58% respectively. Note that the F60° posture underestimates were large; mean error was about 30°, or greater than 50% of the actual angle.

3.3. Observed error

Error, calculated as the absolute value of the difference between the actual and observed angles, is shown for each posture and view in Table 3. For extreme postures, mean error for extension (E90°) ranged between 6 and 30° and 2 and 27° for flexion (F90°) depending on the view angle. The mean error for mid-range postures (F/E: 30°, 45°, 60°) ranged from 5 to 20°. For the neutral posture, mean error was lower, ranging between 0.2 and 4°. The overall mean error for each view across all postures is shown on the right side of Table 3.

A 9 (Wrist Angle) × 10 (View) analysis of variance for repeated measures was conducted in SPSS. Significant main effects of Wrist Angle and View and an interaction effect all at $p < 0.0001$ were found.

The mean error ranged between 7° and 14° across views or about 8% of the wrist range of motion, showing that participants understood task requirements. The main effect of View, $F(9,225) = 13.3$, $p < 0.0001$, was significant; the ideal views (Radial, Ulnar) had significantly lower error than all in-line views, supporting the hypothesis that ideal views produce more accurate estimates. Off-axis views (Fig. 5a, b) also had lower mean error than the in-line views. Interestingly, accuracy in the Radial Dorsal 25° view was at a similar level as the ideal views. The main effect of Wrist Angle, $F(8,200) = 26.1$, $p < 0.0001$, was attributed to the high accuracy of observations of the neutral posture. The interaction effect, $F(72,1800) = 6.4$, $p < 0.0001$, meant that some postures were rated more accurately in some views compared to others.

3.4. Radial and ulnar deviation

This section presents results for observations of wrist deviation. Actual, apparent, and observed wrist angles are shown in each chart in Figs. 6 and 7. Radial deviation is shown as negative and ulnar deviation as positive.

In the ideal views, Dorsal and Palmar (Fig. 6a), the actual angles were included within one standard deviation of the mean observed values. Overall, accuracy was highest for these views, with mean

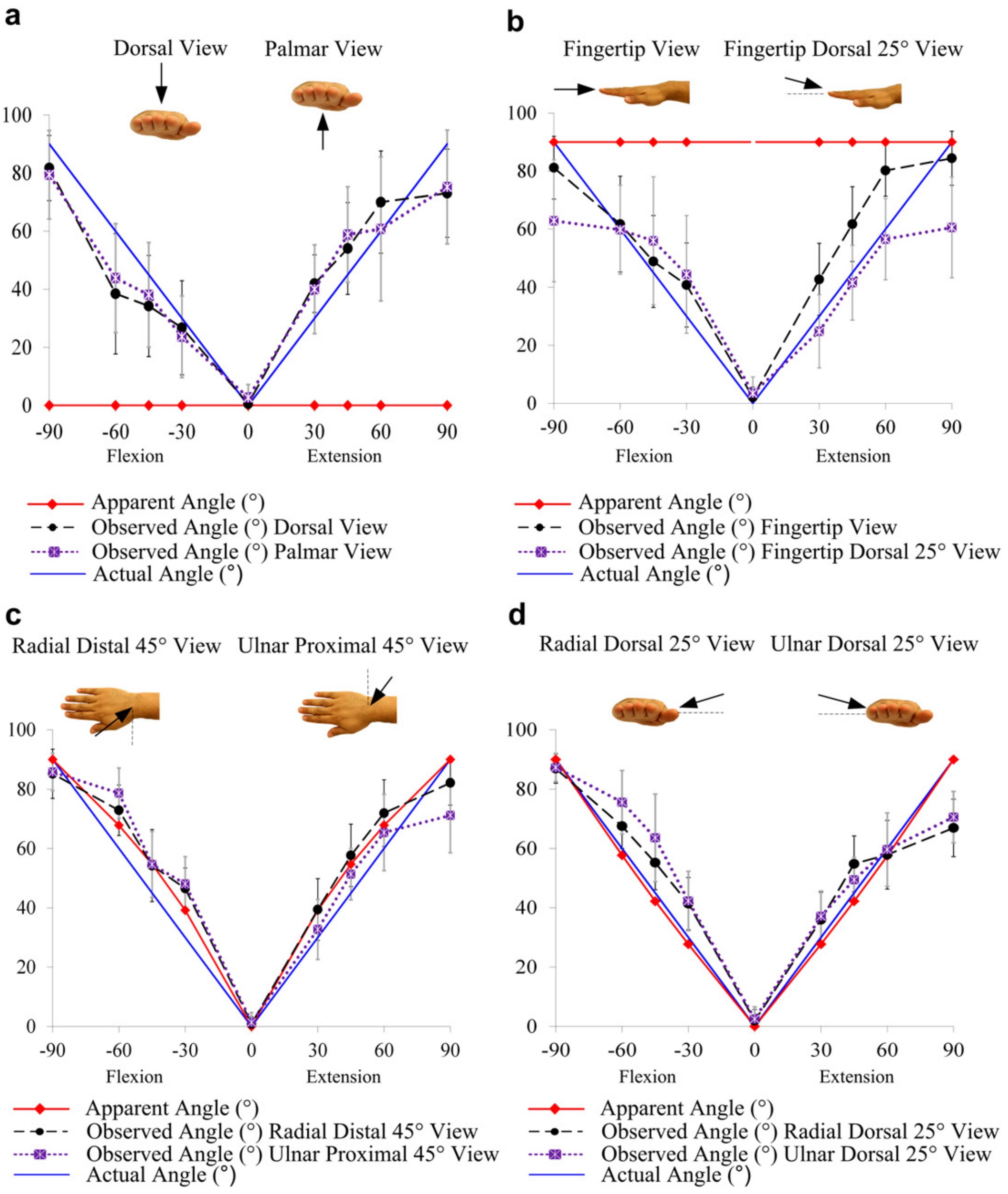

Fig. 5. In-line and off-axis views – actual, apparent, and mean estimated angles (±1SD) are shown (in °) for F/E postures.

Table 1
Proportions of underestimation, overestimation, and exact observations for wrist flexion and extension postures by viewing angle.

	Ulnar[a]	Radial[a]	Dorsal	Palmar	Fingertip	Ulnar distal 45	Radial proximal 45	Radial dorsal 25	Fingertip dorsal 25	Ulnar dorsal 25
Underestimation	23%	43%	43%	44%	46%	14%	41%	23%	53%	32%
Overestimation	44%	38%	28%	28%	41%	50%	39%	42%	33%	35%
Exact	33%	19%	29%	28%	13%	36%	20%	35%	14%	33%

[a] Ideal view; $n = 234$ for each viewing angle.

Table 2
Proportions of underestimation and overestimation of observations and mean error for wrist extension and flexion by posture.

	E90°	E60°	E45°	E30°	F30°	F45°	F60°	F90°
Underestimation	58%	17%	5%	45%	27%	37%	68%	42%
Mean (SD)	18 (5)	14 (9)	13 (3)	20 (14)	14 (3)	14 (7)	31 (17)	16 (8)
Overestimation	28%	64%	77%	42%	47%	39%	18%	0%
Mean (SD)	19 (5)	19 (7)	19 (6)	15 (3)	16 (4)	16 (7)	15 (3)	–

$n = 260$ for each posture.

Table 3
Mean error (SD) in degrees by viewing angle and posture for wrist flexion/extension.

Viewing angle	E90°	E60°	E45°	E30°	N0°	F30°	F45°	F60°	F90°	Mean
Ulnar[a]	20.4 (11.2)	7.5 (7.6)	5.2 (6.5)	10.2 (6.8)	0.2 (1.0)	11.9 (7.2)	8.1 (8.7)	9 (6.6)	3.1 (7.4)	8.4 (7.0)
Radial[a]	20.6 (9.9)	7.3 (7.0)	12.9 (9.4)	15.0 (5.3)	1.7 (3.4)	10.7 (6.6)	7.7 (7.5)	7.1 (7.9)	3.5 (6.3)	9.6 (7.0)
Dorsal	16.9 (15.2)	16.5 (11.4)	12.9 (12.7)	12.7 (8.8)	0.6 (2.1)	15.2 (5.7)	16.1 (12.3)	25.4 (15.5)	8.3 (11.2)	13.8 (10.6)
Palmar	14.8 (19.6)	18.8 (15.6)	17.7 (12.0)	13.8 (11.8)	2.7 (4.5)	12.9 (8.1)	14.6 (12.3)	20.8 (13.2)	10.6 (15.2)	14.1 (12.5)
Fingertip	6.3 (8.8)	20.2 (8.9)	16.7 (12.9)	13.8 (11.1)	2.1 (3.5)	13.8 (11.4)	9.2 (13.3)	13.3 (9.6)	8.8 (10.8)	11.6 (10.0)
Ulnar Distal 45	7.9 (7.5)	13.1 (9.8)	12.7 (10.5)	10.2 (9.6)	0.9 (2.3)	16.5 (6.9)	9.6 (11.8)	12.9 (8.5)	4.8 (8.3)	9.8 (8.4)
Radial Proximal 45	18.8 (12.6)	10.8 (8.7)	7.9 (7.2)	8.1 (6.5)	1.3 (3.3)	18.0 (9.2)	10.0 (10.8)	19.0 (7.5)	4.2 (6.3)	10.8 (8.0)
Radial Dorsal 25	23.1 (9.7)	9.0 (7.3)	9.8 (9.4)	9.0 (6.2)	1.9 (3.8)	11.4 (8.8)	10.6 (8.6)	7.5 (7.5)	3.1 (4.9)	9.5 (7.4)
Fingertip Dorsal 25	19.4 (8.6)	8.8 (8.5)	6.0 (6.3)	7.9 (7.8)	2.5 (4.0)	12.3 (10.0)	19.3 (13.7)	16.7 (8.7)	2.7 (4.7)	7.6 (5.7)
Ulnar Dorsal 25	29.4 (17.3)	11.9 (7.7)	8.8 (9.8)	19.6 (8.4)	3.5 (5.6)	17.9 (17.1)	19.8 (14.2)	11.7 (9.6)	27.1 (21.0)	10.8 (7.2)

[a] Ideal view.

error being about 5° less than for the in-line views. There were large errors in the in-line views (Fig. 6b); overall, the mean error was at least 11° for each of these views. It appeared that observations were more accurate for ulnar deviation when made from the Ulnar view than when made from the Radial view. The other in-line views also did not produce the same results as was predicted by the model, but were instead closer to the measured values (Fig. 6c and d). Errors tended toward underestimation. These results supported

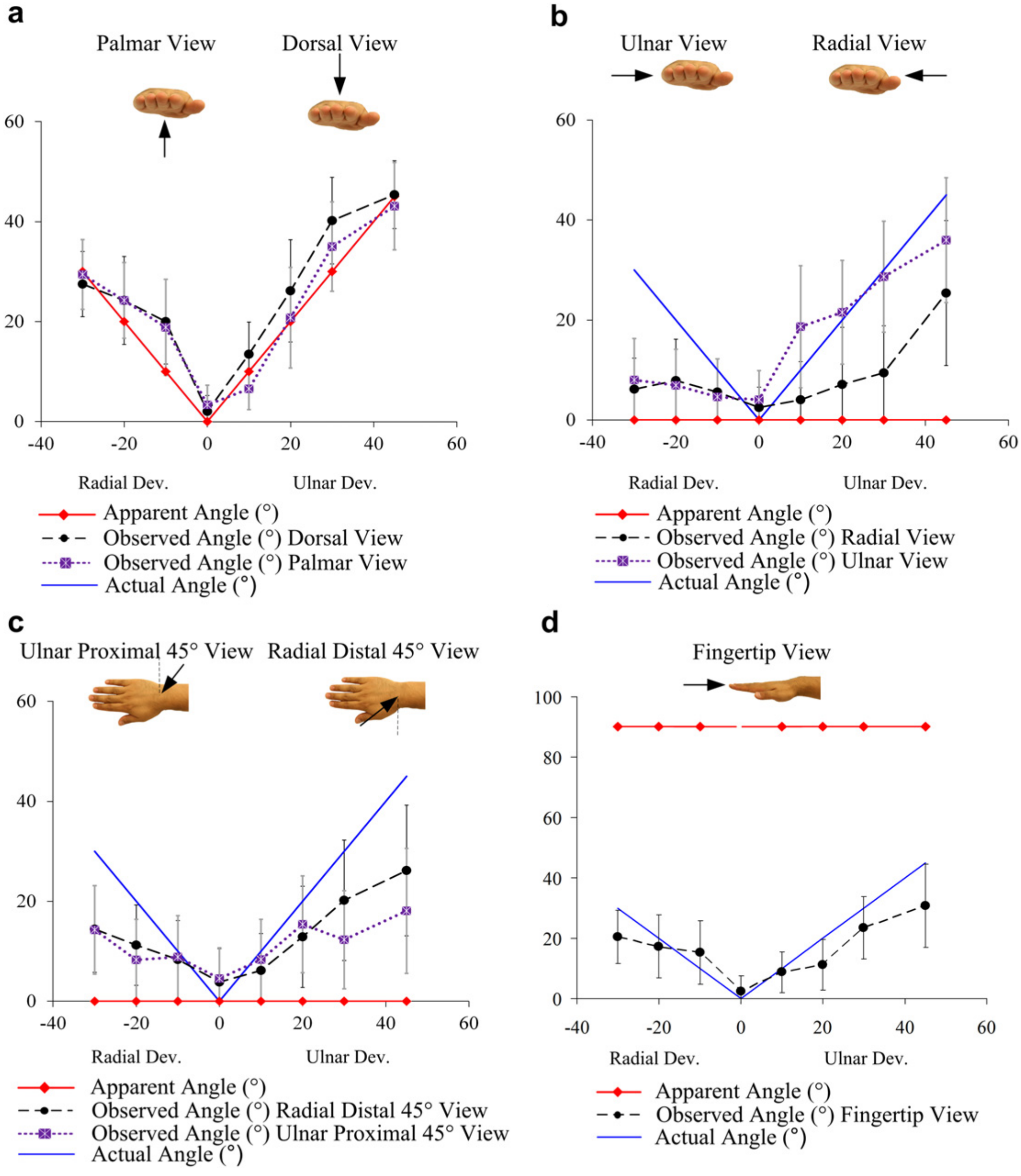

Fig. 6. Ideal and in-line views – actual, apparent, and mean estimated angles (±1SD) are shown (in °) for R/U deviation.

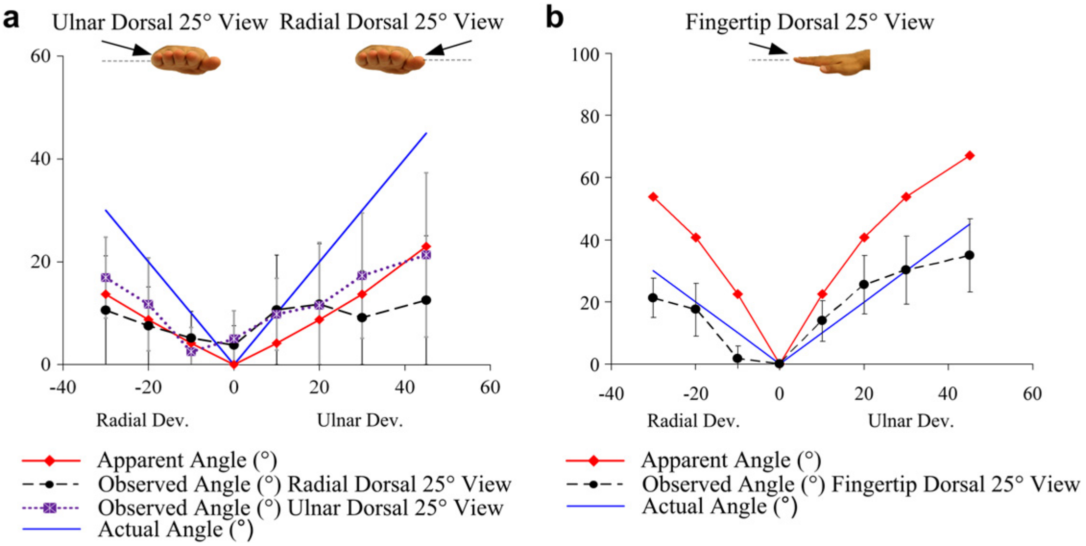

Fig. 7. Off-axis views – actual, apparent, and mean estimated angles (±1SD) are shown (in °) for R/U deviation.

the hypothesis that parallax decreases the accuracy of observer estimates, but not as much as predicted by the model.

In the off-axis views (Fig. 7), there were remarkable underestimations of the angles seen across all postures in the Ulnar and Radial Dorsal 25° views (Fig. 7a). As the posture became more deviated, the error also increased. These followed the values predicted by the model more than the actual angles. The Fingertip 25° view (Fig. 7b) was more accurate that the predicted value, and, similar to the ideal views, the actual angles were encompassed within one standard deviation of the mean observed values.

3.5. *Underestimation and overestimation*

The proportion of overestimation, underestimation, and exact responses are shown by viewing angle in Table 4; the same is shown by posture in Table 5 along with the mean error. In total, 58% of the trials contained underestimates, 21% had overestimates, and 21% had no error. Seven views had >50% underestimation overall; this trend was also reflected when analyzed by Posture. The U45° posture was underestimated (67%) by a mean of 21°. The R30° posture was also underestimated (77%) by a mean of 16°. The overall underestimation seen in the most extreme radial deviation (R30°) posture was greater than half of the actual angle. These underestimation errors in the extreme postures were much less pronounced for the ideal views (<10°).

3.6. *Observed error*

Mean error for deviation postures is shown in Table 6. For extreme postures, mean error for radial deviation (R30°) ranged between 4 and 24° and 4 and 32° for ulnar deviation (U45°). Mean error for mid-range postures (R20°, R10°; U30°, U20°, U10°) extended from 3 to 21°. For the neutral posture, mean error ranged between 0 and 5°. The overall mean error for each view across all postures is shown on the right side of Table 2.

The mean error between all views ranged between 6.2° for the Dorsal view and 14.5° for the Ulnar view, a total difference of 8.3°. This range represented 7–18% of the range of motion. The mean absolute errors demonstrated that the participants were less accurate at estimating deviation than flexion/extension.

An 8 (Wrist Angle) × 10 (View) analysis of variance for repeated measures was conducted in SPSS. Significant main effects of Wrist Angle and View, and an interaction effect all at $p < 0.0001$ were found. The main effect of View, $F(9,225) = 26.3$, $p < 0.0001$ was significant. The ideal views (Palmar, Dorsal) had significantly lower mean errors than almost all other views. The in-line views (Radial and Ulnar) were observed to have the greatest error. The Fingertip and Fingertip Dorsal 25° views had lower mean errors relative to the other non-ideal views. The main effect of Wrist Angle, $F(7,175) = 47.6$, $p < 0.0001$, was attributed to the accurate estimation of the neutral posture, similar to F/E postures. The interaction effect, $F(63,1575) = 8.9$, $p < 0.01$, also showed differences between specific postures and views.

4. Discussion

4.1. *The effect of parallax*

Viewing angle was observed to affect the accuracy of wrist posture estimation from static images. Based on the data obtained in this study, the hypothesis that there was no difference between observer and predicted parallax error was rejected. In fact, observers performed better than the model predictions. These findings have implications for observational analysis of wrist posture.

Parallax effects were shown to be non-uniform between views, as predicted by the model. As expected, the ideal views produced the

Table 4
Proportions of underestimation, overestimation, and exact observations for radial and ulnar deviation by viewing angle.

	Ulnar	Radial	Dorsal[a]	Palmar[a]	Fingertip	Ulnar distal 45	Radial proximal 45	Radial dorsal 25	Fingertip dorsal 25	Ulnar dorsal 25
Underestimation	74%	54%	28%	18%	54%	66%	64%	67%	43%	62%
Overestimation	7%	24%	38%	50%	19%	14%	11%	12%	22%	14%
Exact	19%	22%	36%	32%	27%	20%	25%	21%	35%	24%

[a] Ideal view; $n = 182$ for each viewing angle.

Table 5
Proportions and means of underestimation and overestimation of observations and mean error for radial and ulnar deviation by posture.

	R30°	R20°	R10°	U10°	U20°	U30°	U45°
Underestimation	77%	67%	49%	37%	55%	54%	67%
Mean (SD)	16 (5)	11 (3)	9 (1)	8 (12)	11(4)	15 (5)	21 (6)
Overestimation	3%	20%	29%	28%	30%	24%	16%
Mean (SD)	12 (2)	10 (2)	9 (4)	12 (6)	12 (3)	12 (4)	5 (1)

$n = 260$ for each posture.

most accurate observations for both flexion and deviation type postures. Observations from the in-line views were the least accurate, but interestingly were still better than the predicted values. Bao et al. (2009) described large between-rater variations when "dorsal" views were used for F/E and "side" views were used for R/U deviation. Because the parallax model is limited to 2D and did not provide insight into how people estimate postures in 3D, we construe that the raters were using other visual information, such as the relative length of the hand segment or the visibility of the fingers.

The parallax model appeared to be effective at explaining the observations from some of the off-axis lateral views (Radial Distal 45° and Ulnar Proximal 45° for F/E, and Ulnar Dorsal 25° and Radial Dorsal 25° for R/U). For F/E, there may not have been a large enough change in view angle in the two Dorsal 25° views to alter the images significantly from the ideal views, which supports the idea that greater observation error is associated with viewing angles with larger perspective error. The neutral posture was estimated the most accurately and did not appear to be affected by parallax. The neutral wrist appeared as a straight line or a "point" regardless of view, which may be more easily recognized by raters.

4.2. Relative accuracy

In absolute terms, observer accuracy was similar between posture types in that the range of mean error between views was similar for wrist flexion/extension and deviation. However, deviation has a much smaller range of motion (ROM). This error expressed as a percentage of ROM for F/E is approximately 12%. For deviation, this error is about 23% of ulnar deviation ROM and 34% for radial deviation ROM. By view, the mean error ranged between 21% (Dorsal) and 48% (Ulnar) of the ROM for radial deviation. If similar errors are present in existing studies using observational methods, the prevalence of the more extreme deviation postures may be largely underestimated.

4.3. Underestimation and overestimation

Disparity was also seen in tendencies to underestimate or overestimate postures. In F/E, wrist angles were overestimated 39% and underestimated 38% of the time. Mean overestimation error was consistently near 15°, but underestimation error varied more (10–25°) depending on the view angle. Certain postures were more affected than others; E45° was overestimated 77% of the time ($\overline{X} = 19^\circ$) while F60° was underestimated 68% ($\overline{X} = 15^\circ$). Note the proximity of these poorly estimated mid-range postures to cut points used for previously mentioned observational methods.

In wrist deviation there was a much greater tendency to underestimate (58%). Underestimation varied by view and by posture, with mean error increasing for more extreme wrist angles. The largest mean underestimation error occurred in the Radial view ($\overline{X} = 17^\circ$). Underestimation was lowest for the two ideal views (Dorsal and Palmar) ($\overline{X} = 8^\circ$). Overestimation (22%) was very consistent across views and postures ($\overline{X} = 10^\circ$).

4.4. Wrist deviation

The results of wrist deviation estimation show errors being exacerbated by non-ideal view angles and degree of posture. This suggests that at least novice raters are unable to estimate wrist deviation with the accuracy required for either practical or research purposes without knowledge of the view angle.

These results confirm existing research reported by Lowe (2004), who analyzed the accuracy of estimates of peak and mode wrist postures from video using a 3-category scale (20° F/E and 10° R/U deviation cut points) and a 6-category scale (20° and 45° F/E and 10° and 20° R/U deviation cut points) and found significant misclassification. Error was primarily underestimation, especially for the extreme postures. Ketola et al. (2001) also noted that their observers underestimated the prevalence of non-neutral postures according to a 20° cut point; poor validity in comparison to wrist goniometry data was also reported.

4.5. Use of other visual cues

From the data, it appears that the parallax model does not explain the variation seen in the in-line views where raters did not estimate all the postures as the same. Participants likely integrated other visual cues into their judgments because unlike the model, the wrist is not a simple stick figure. For example, in observations from the Ulnar view, ulnar deviation was more accurate than radial deviation, but this was not seen using the Radial view. Further investigation into which cues are being used is warranted.

An alternative explanation is that the camera angle may not have been perfectly in line with the axis of rotation, in which case the model predicts small, but different apparent angles for each posture.

4.6. Research implications

A collective underestimation of exposure to extreme postures would weaken or mask relationships between wrist posture and musculoskeletal disorders. These results converge with the lack of

Table 6
Mean error (SD) in degrees by viewing angle and posture for wrist radial/ulnar deviation.

Viewing angle	R30°	R20°	R10°	N 0°	U10°	U20°	U30°	U45°	Mean
Ulnar	22.0 (8.3)	13.5 (6.3)	8.1 (4.5)	4.0 (5.8)	11.0 (10.1)	8.5 (6.0)	8.3 (7.3)	14.0 (12.5)	14.5 (6.9)
Radial	23.8 (6.2)	12.9 (7.0)	6.7 (4.2)	2.5 (4.1)	8.6 (4.1)	16.0 (6.2)	20.6 (9.4)	24.6 (14.5)	11.2 (7.6)
Dorsal[a]	4.4 (5.3)	6.9 (5.1)	8.8 (9.6)	3.3 (3.9)	3.8 (3.7)	7.7 (6.4)	8.1 (6.2)	6.9 (8.7)	6.2 (6.1)
Palmar[a]	4.4 (5.3)	8.5 (4.6)	10.0 (8.5)	2.0 (3.2)	4.6 (5.6)	9.2 (7.4)	11.3 (7.0)	4.6 (6.8)	6.8 (6.1)
Fingertip	10.7 (7.3)	8.8 (5.9)	8.3 (8.2)	2.3 (5.1)	5.5 (4.0)	10.0 (6.9)	8.8 (8.4)	19.2 (13.7)	9.2 (7.4)
Ulnar distal 45	15.7 (8.8)	12.5 (6.8)	6.9 (4.5)	4.5 (6.1)	6.3 (5.2)	8.5 (6.4)	18.1 (9.1)	31.9 (12.5)	13.0 (7.4)
Radial proximal 45	15.6 (8.6)	10.3 (5.7)	5.9 (5.2)	3.8 (6.7)	5.7 (5.9)	10.2 (6.8)	13.3 (7.9)	23.8 (13.1)	11.1 (7.5)
Radial dorsal 25	13.1 (7.9)	10.2 (6.7)	8.3 (3.1)	5.0 (5.5)	4.8 (5.0)	13.5 (6.0)	14.2 (10.3)	28.6 (16.0)	12.2 (7.5)
Fingertip dorsal 25	8.6 (6.2)	7.1 (5.1)	8.6 (3.0)	0.0 (0.0)	5.0 (5.6)	7.9 (7.5)	8.6 (6.4)	15.0 (11.8)	7.6 (5.7)
Ulnar dorsal 25	16.7 (9.3)	10.3 (6.4)	6.3 (4.1)	2.9 (3.8)	6.5 (8.4)	10.2 (5.6)	8.5 (7.3)	24.8 (12.5)	10.8 (7.2)

[a] Ideal view.

evidence of a strong relationship between epidemiological findings and exposure estimations. Observational studies should be examined for parallax effects by analyzing viewing angles used in data collection methods.

Based upon these results, the use of cut-points in observational methods may i) be ineffective and/or ii) less meaningful due to their susceptibility to parallax. For example, the Rapid Upper Limb Assessment by McAtamney and Corlett (1993) uses a 15° cut point for wrist deviation. It could be estimated that from a non-ideal viewing angle (e.g. Ulnar view), deviation postures up to 33° could be misclassified as not increasing risk, i.e. 83% of an assumed 45° ROM. The Strain Index (Moore and Garg, 1995) moved away from cut-points to a scale with verbal anchors loosely based on cut points proposed by Stetson et al. (1991) and Armstrong et al. (1982), which may be more appropriate.

New cut-points can be recommended based upon the observed error levels. For wrist flexion/extension, analysts might be expected to categorize using 5 cut-points [−65°; −30°; 0°; +30°; +65°], which may produce better inter-rater reliability. These intervals correspond approximately in size to those recommended by Bao et al. (2009). For ulnar and radial deviation, analysts may only be able to categorize acceptably at verbal anchors of neutral (0°), non-neutral (>0°), and maximum (end-range).

4.7. Limitations and further study

The simulated conditions in this study do not reflect field conditions for visual recording of workers. This study included a finite number of well-defined postures, close-up views, constant image size, consistent background, and adequate lighting. These conditions may not be readily attainable where camera positioning depends upon the task, environment, and worker movement, or is often complicated by limited space, obstructions, and/or a need to avoid work interference. Wrist posture estimation errors may be larger under real life conditions.

Work objects may affect the ability to estimate posture. The relative size of a part may provide additional depth cues. Objects that change the hand posture (e.g. gripping) may increase the probability of certain hand postures (e.g. extension), which could be useful for the analyst. They could also mask view of the hand, making it more difficult. There may also be a need to study additional hand sizes, aspect ratios, and skin colors.

The wrist is a relatively small joint. Obtaining large wrist images may conflict with a desire to capture whole body images. Accuracy is expected to be even more affected by parallax in this case. The effect of parallax of postural evaluation of larger joints merits further study.

The study was designed to eliminate the need for experienced participants, but analyst experience may still have an effect. Lowe (2004) found no clear effect of analyst experience on the accuracy of posture estimates. A study of surgeons and trainees showed that experienced surgeons were more adept at perceiving elaborate 3-D structures from 2-D images than were trainees (Sidhu et al., 2004), but the effect was smaller after trainees received training. Experience may influence posture estimation if a viewing angle is known; experienced analysts may be more adept at accounting for parallax and obtaining meaningful cues from movement and/or task knowledge. Still, it is difficult to know the exact viewing angle without measuring it, even with direct observation. Without knowledge of the view angle "experts" likely are as susceptible to parallax effects as the naïve observer, possibly explaining the similarities Ketola et al. (2001) observed between experts and non-experts.

In this study observers did not differentiate between flexion and extension or between radial and ulnar deviation. The two posture types were also considered independently, even though they often occur at the same time. Furthermore, forearm rotation was not considered in this study. In actuality, analysts do need to integrate these factors and decide how to categorize postures. Viewing angle may affect this task and the resulting accuracy may be worse in real wrist posture estimation situations.

A single viewing angle cannot capture all the ideal angles when more than one posture type is being evaluated simultaneously. Even when multiple views are being used in synchrony, care must be taken to obtain as much footage from ideal angles as possible. Techniques to control for parallax effects when recording in occupational environments are needed and, based upon our results, include i) recording from the ideal view for the posture type, ii) measuring view angles, and iii) providing (simultaneous) views from multiple angles to maximize the opportunity to capture the ideal view.

5. Conclusion

Novice raters are able to estimate wrist flexion/extension angles remarkably well given good image capture conditions, but are nevertheless susceptible to the effect of different viewing angles. Researchers and practitioners need to control systematically for parallax when collecting and using photographic data for posture analysis. Capturing from ideal views for the posture in question is recommended, in-line views should be minimized, and using multiple cameras is preferred even if not synchronized. Documentation of methods for image capture should be detailed sufficiently that others may interpret possible effects of parallax. Future investigation of the effect of off-axis views is recommended. Training analysts on minimizing parallax effects in image recording may improve the accuracy of observational estimates of wrist posture both from ideal and non-ideal viewing angles.

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