2015

Precision and repeatability of the Motion Analysis Corporation digital motion capture system

Maria Reinbolt

Precision and Repeatability of the Motion Analysis Corporation Digital Motion Capture System

Maria Reinbolt

Research Advisor: Martin Rice, Ph.D., OTR/L, FAOTA

Occupational Therapy Doctoral Program

Department of Rehabilitation Sciences

The University of Toledo

Note: This scholarly project reflects individualized, original research conducted in partial fulfillment of the requirements for the Occupational Therapy Doctoral Program, The University of Toledo.

Abstract

The goal of this study was to establish measurement fidelity for the Motion Analysis Corp. digital motion capture system and thereby substantiate the validity of motion capture research in occupational therapy. This was a mixed research design study completed at the motion capture lab at the sponsoring university. Repeatability data were collected in two identical sessions, two weeks apart. There were two sets of conditions in each session: marker sizes and sample rates. Precision data were collected on a different session using the same combinations of conditions. A Motion Analysis Corp. Digital 8-camera motion capture system with Cortex, v. 5.0.1.1497 and C-Motion's Visual3D data reduction software was used to prepare the data for statistical analysis. SPSS software v 21 was used to statistically analyze the data. The analysis for repeatability involved a repeated measures ANOVA and precision was assessed for each condition utilizing a MANOVA. For both length and angle, no significant differences were found between Trial A and Trial B when testing repeatability. The precision of each dependent variable was affected by specific combination of conditions that were present in the study with mixed results of statistical significance. The results demonstrate that the Motion Analysis Corporation Digital motion capture system is highly precise and repeatable. Future research should investigate other motion capture systems to ascertain measurement fidelity.

Precision and Repeatability of the Motion Analysis Corporation Digital System

Motion capture has become ubiquitous among studies done on human movement and biomechanics. Previous studies include, but are not limited to clinical gait analysis (Carse, Meadows, Bowers, & Rowe, 2013), measurement of finger flexion and extension (Rash, Belliappa, Wachowiak, Somia, & Gupta, 1999), and kinematics involved with safe patient handling (Bartnik & Rice, 2013). The degree to which motion capture is used is extensive and continues to grow in the study of human movement (States & Pappas, 2006). There are a number of motion capture systems available ranging in price, quality, and application. Among the available systems, there are about 5 prominent companies in the field: Motion Analysis Corporation (Motion Analysis, Santa Rosa, CA), Optotrak (Northern Digital, Waterloo, Canada), Vicon (Vicon, Oxford, United Kingdom), Qualysis (Qualysis AB, Gothenburg, Sweden), and CODA (Charnwood, Leicestershire, United Kingdom).

Motion capture is utilized in a variety of ways, some of which include surgical navigation, medical robotics, video game production, and rehabilitation. In all applications, precision of the systems used to capture human motion is essential in achieving accurate reconstruction of human joint kinematics, which is the end objective (Chiari, Della Croce, Leardini, & Cappozzo, 2005). Despite the importance of precision and repeatability of motion capture systems, there are surprisingly few studies that delve into the topic. The most widely cited study was performed by James Richards (1999) where he compared eight motion capture systems against each other. The study analyzed seven different motion capture systems in four ways: a) accuracy of distance measurement between two moving markers, b) measurement of motion associated with a static marker, c) marker reconstruction abilities of the software associated with the system, and d) the system's ability to measure the motion of one marker that moved in close proximity to another marker. The study included six passive marker systems and one active marker system.

Passive markers are retro-reflective and are paired with light emitting (typically infrared) cameras to create a three-dimensional picture. Because passive markers are reflective, no wires or attachments are necessary to communicate their respective positions to the cameras. Based on the placement of the markers, the cameras' associated software is what tracks the data to construct the three-dimensional image (Chiari et al., 2005). Certain systems' software has the capability for the operator to manually re-identify markers that were initially misidentified by the software (Richards, 1999). Active markers are infrared light emitting diodes that employ a current of pulsed light and show up to their cameras as very bright spots on the image. The pulsing is timed sequentially with camera detection allowing the markers to always be correctly identified by the associated software, therefore, no re-identification is necessary (Durlach & Mavor, 1994). In order for the active markers to be sequential with the cameras, the markers have to physically be connected to their cameras via wires.

There is some debate about what type of marker system is more accurate, the winner typically being active markers (Chiari et al., 2005; Durlach & Mavor, 1994; Wiles, Thompson, & Frantz, 2004). However, Wiles et al. (2004) explained that this is a widely held misconception. They performed a comparison of active markers and passive markers utilizing the same motion capture system (Polaris, Northern Digital, Waterloo, Canada). The results indicated that there was no statistically significant difference between the accuracies of the two marker types. They attribute the misconception to the lack of understanding of the statistical principles behind spatial measurement systems, which are non-Gaussian by nature. Richards' (1999) study also showed that the active marker system, CODA, did not perform better than all of the passive marker systems. Overall, the purpose of the study was not to conclude that one system was dominant over another, instead to display the results of the analysis as well as additional information regarding editing and software capabilities.

Software is the essence of motion capture and its primary goal is to construct 3-D coordinates of its object's markers from the 2-D data its cameras provide (Chiari et al., 2005). There are five main factors that contribute to the motion capture software's ability to collect, analyze and output meaningful data. These factors are: (a) initialization, (b) marker detection, (c) spatial correspondence, (d) temporal correspondence, and (e) post-processing (Guerra-Filho, 2005).

Initialization is the process of camera calibration utilizing both intrinsic and extrinsic parameters. Intrinsic parameters determine how the image coordinates of an object are mapped onto the image sensor of the camera by controlling how light is projected through the camera lens. Extrinsic parameters measure the position and orientation relationship between the cameras and the coordinate system in their environment or between different cameras (Salvi, Armangué, & Batlle, 2002). Marker detection involves mathematical algorithms that detect the brightness of the markers against their background and therefore determine the 2-D pixel coordinates of the markers (Chiari et al., 2005).

Spatial correspondence is essentially what reconstructs the 2-D captures into 3-D points and is also attributed to mathematical algorithms. Each detected marker in an image has a determined 2-D point on an image plane. If two or more cameras have matched 2-D points, they are reconstructed into a 3-D point (translational data) (Guerra-Filho, 2005). This leads to temporal correspondence, which tracks the timing relationship between where a single 3-D point is from one camera frame to the next (Guerra-Filho, 2005). A tracking algorithm then allows the system to connect the 3-D points and results in the construction of 3-D trajectories (Gruen, 1997). After the data are collected and analyzed, post-processing is necessary to complete the motion capture analysis. Operator intervention is typically needed to label markers and their trajectories for identification purposes, as well as to find missing markers and correct possible detection errors (Guerra-Filho, 2005). Missing markers and detection errors may be attributed to a system's inability to distinguish neighboring markers or to visibility constraints where the marker was not detected at all. This can be fixed by the user, but does increase post-processing time (Chiari et al., 2005).

There are many physical components that are necessary to make human motion capture possible. The object being studied, the markers, and the cameras are all essential to the process, but would have no application without the software. It is important to consider all of the aspects of motion capture to appreciate the complexity of the information collected and how it is transformed into meaningful information to be used clinically.

There are a few other studies that have been done to analyze the accuracy of specific motion capture systems, though none have been as comprehensive as Richards'

(1999) and most have focused on the companies Northern Digital and Vicon. Thewlis, Bishop, Daniell, and Paul (2013) conducted a study comparing the statistical and linear accuracy and gait kinematics of one high-cost motion capture system (Vicon, Oxford, United Kingdom) to a lower cost system (Optotrak, Northern Digital, Waterloo, Canada). Referring to the accuracy of higher-cost systems, Thewlis et al. (2013) believe the results of Richards' study have significantly contributed to the knowledgebase in motion capture systems, but the biomechanics community accepts that the technology and accuracy of motion capture systems have probably improved since Richards' study. They further explained that while there has been a comprehensive study done on high cost motion-capture systems by Richards, there has been no study done on the lower cost systems to examine accuracy, hence the need for their study.

Two separate experiments were conducted by Thewlis et al. (2013) and the results were analyzed separately. The experiment measuring statistic and linear accuracy found the Optotrak system produced more errors than the Vicon system, though no absolute percentage error was greater than 1% of the known length. Regarding the gait kinematics experiment, 4.2° was the largest absolute difference between the two systems, and only four other variables resulted in an absolute difference greater than 3° but less than 4°. The authors believe that the findings of their experiments suggest that the use of low-cost motion capture systems is acceptable due to the minimal difference in the accuracy of the systems. They also explained that both the high-cost and low-cost systems both performed better than their earlier counterpart evaluated in Richards' study done in 1999, which they attribute to enhancements in tracking algorithms.

Another study was done comparing the Optotrak system to two different Vicon systems by Carse et al. (2013). Specifically with regards to gait analysis, they conducted a study to determine the marker tracking accuracy of the low-cost Optotrak system as compared to an older, but well established Vicon system (612) as well as another newer, high-cost Vicon system (MX). The Vicon 612 system was referred to in the Vicon Manual (Tebbutt, Wood, & King, 2002) and the Vicon MX system was referenced in the Vicon MX Hardware System Reference (Vicon, 2006). The purpose of their study was to address the need in gait analysis for an affordable system with acceptable accuracy of markers during over ground walking. The authors reported that the three systems results were generally in agreement, with a minimal difference in vector magnitude, between 1-3mm. There were some gaps in the trajectory for the Optotrak and Vicon 612 systems, but the higher end Vicon system reported no gaps. Even with the minimal differences, Carse et al. (2013) still concluded that the lower end system was an acceptable solution to deliver accurate marker tracking during gait analysis when compared to the older, widely used, higher cost Vicon 612 system.

A variety of applications for motion capture can be found in the entertainment field as well. Most movies and video games that have human-like characters with realistic motion are employing the technology of motion capture (Geroch, 2004). Movie studios use motion capture to animate background motions during crowd scenes and to provide motions to non-human creatures. As an example, the character in *Lord of the Rings*, Gollum, is one of the most memorable examples of using motion capture to animate a computer-generated character (Allison, 2011). Video game companies have also capitalized on motion capture technology. These companies record sport-stars performing their signature moves and then integrate them into the video game. In addition, they collect and store fragments of natural motion that can be re-ordered and utilized real time during game playing (Bregler, 2007).

In addition to the enhancement of the entertainment industry's virtual reality games and character construction, there are many clinically valuable applications for human motion analysis. Developments in augmented reality are being used in breast biopsy and laparoscopic procedures via motion tracking technology at UNC-Chapel Hill (Welch & Foxlin, 2002). Mannion and Troke (1999) highlighted the necessity of motion capture in the case of patients with spinal injuries. They argued that the precision and repeatability of motion capture systems is vital to determining the extent of a patient's injury, whether or not rehabilitation is necessary, and if they can suitably work. Tracking surgical instruments (surgical navigation) in the operating room is another widely employed application of motion capture. Ewers et al. (2005) performed a study evaluating the medical benefit and technical expenditure of using surgical navigation in a variety of craniomaxillofacial procedures. The results of the study, they report, indicated that the medical benefit outweighs the technical expenditure for the majority of the procedures in the study. Further, the authors state that the use of the technology reduces time and the overall cost to prepare for and perform certain surgical procedures (Ewers et al., 2005).

Looking specifically at occupational therapy, motion capture has been and continues to be used for a wide variety of research topics (e.g., Bartnik & Rice, 2013; Cooper, Shwedyk, Quanbury, Miller, & Hildebrand, 1993; Feng & Mak, 1997; Nakamura, Abreu, Patterson, Buford, & Ottenbacher, 2008; Rice & Thomas, 2000;

Trombly & Wu, 1999; Wu, Chen, Tang, Lin, & Huang, 2007). Shurtleff, Standeven, and Engsberg (2009) used motion capture to evaluate head and trunk stability as well as functional reach in children with spastic diplegia cerebral palsy after hippotherapy. A pre-test/post-test research model was applied. While sitting on a mechanical barrel, dynamic stability in the sagittal plane was used as the determinant for head and trunk stability while the pelvis was moving. The authors evaluated this stability with the motion capture system by using the tracked data of head angle and anterior posterior translation of the spine and head. The functional reach of the subjects was assessed by elapsed time of the movement and the reach path using motion capture to determine the directness of the path and the timing of the reach. The results of this study indicated that children with spastic diplegia cerebral palsy had increased motor control of their head and trunk. In turn, this may have accounted for the improvements in the functional reach test of the subjects. Further, these improvements were shown to persist for at least three months post intervention.

Another way motion capture has been employed to evaluate reach in occupational therapy is to measure the quality of movement. In a study done by Rice and Thomas (2000), motion capture was used to evaluate quality of movement by measuring movement time, displacement, peak velocity, percentage of movement time to peak velocity, and movement units. This counterbalanced, repeated measures design evaluated the effects of perceived risk on occupational performance while pouring hot and cold water. The dependent variables listed above were measured using motion capture while the study participants were pouring a cold beverage and then a hot beverage. The study found that during the hot pour, the movement time, displacement, and motor units were significantly greater than during the cold condition showing that the quality of movement was better when the participants were pouring the cold water. The ability to precisely measure the dependent variables listed above allowed the authors to objectively analyze how perceived risk could impact a subject's performance. Rice and Thomas (2000) discuss the implications of the study and suggest that the research findings can be directly applied to occupational therapy practice. They explain that introducing different levels of risk to a client may help them experience and develop appropriate movement patterns to be successful in everyday occupations.

Therapeutically, motion capture gives practitioners another tool to determine the direction and effectiveness of therapy. A study done by Feng and Mak (1997) focused on spastic voluntary elbow movement. They explain that motion capture allows clinicians to refer back to data and review disordered movements as well as allowing for quantitative evaluation body kinetics and kinematics. Feng and Mak (1997) also believed that parameters obtained through motion capture studies could possibly be applicable to evaluating the efficacy of various therapeutic interventions. Motion capture also plays a significant role in monitoring a patient's mobility during therapy. Changes in an individual's spinal movement can only be accurately measured by equipment that produces precise and repeatable measurements, like motion capture (Mannion & Troke, 1999). Practitioners who perform and interpret gait analysis have also utilized motion capture technology. Motion capture allows clinicians to obtain quantified assessments of their patients' gait patterns and apply that information to manage their patients respective pathologies (Davis, Ounpuu, Tyburski, & Gage, 1991). Understanding body movement and the ability to quantify how a patient moves will help therapists deliver more appropriate and specific treatment options to their patients (Coutts, 1999).

The purpose of this study is to determine the precision and repeatability of the Motion Analysis Corporation Digital motion capture system. While there are a number of studies that look at individual motion capture systems, there is a large void in research on the Motion Analysis Corporation motion capture system, and this paper will address that void. A study to evaluate the Optotrak 3020 system was done by States and Pappas (2006) and many of their parameters were used in this analysis. As in the previous study, various positions and angles were measured in two conditions: motion and static. The angle of four markers and the distance between two markers was evaluated with regards to the precision and repeatability of the measurements. New to this study was the assessment of different sized passive markers (.5 inches and .75 inches) as well as different sample rates (100Hz, 200Hz). All combinations of conditions were evaluated to find the highest level of precision and repeatability of the motion capture system to be used in future research studies. We had two hypotheses associated with this study: 1) there would be no statistically significant difference between captured position and angle and actual position and angle of each marker size at each sample rate. This will be true during static and moving trials, and 2) there would be no statistically significant difference between the repeatability measurements of Trial A and Trial B.

Methods

Equipment and Software:

A Motion Analysis Corp. Digital 8-camera motion capture system (7 Owl cameras and 1 Raptor camera) with Cortex, v. 5.0.1.1497 (Motion Analysis Corporation, Santa Rosa, CA) and C-Motion's Visual3D data reduction software was used to prepare the data for statistical analysis. SPSS software v 21 was used to statistically analyze the data. The analysis for repeatability involved a repeated measures ANOVA and precision was assessed for each condition utilizing a multivariate analysis of variance (MANOVA).

Procedures:

Data were collected in two identical trials (A and B), one week apart, to measure the repeatability of the system. There were two sets of conditions in each session: marker sizes and sample rates. The marker sizes were .5-inches and .75-inches and the sample rates included 100Hz and 200Hz. Two marker size conditions and two sample rate conditions were tested in both Trials A and B: (a) Small/Slow (SS) -- .5-inch marker and 100Hz; (b) Small/Fast (SF) -- .5-inch marker and 200Hz; (c) Large/Slow (LS) -- .75-inch marker and 100Hz; and (d) Large/Fast (LF) -- .75-inch marker and 200Hz. All of these combinations had four markers attached to a 40cm x 60cm right angle carpenter square using double-sided tape (Figure 1). Three carpenter squares were utilized during the investigation: 1) carpenter square with small markers used during repeatability and precision trials, 2) carpenter square with large markers used only for the repeatability trials, and 3) carpenter square with large markers used only for the precision trials. Different carpenter squares were used so the markers would never have to be removed when testing large verses small markers. This decreased the chance for human error in replacing the markers in the exact position. The carpenter square was mounted on a stationary platform to divert from human error while holding the carpenter square. The arrangement of the markers was similar to how the motion of the shoulder or elbow would be measured. There are two dependent variables associated with length, a) the distance between the corner marker and the long arm marker (LAD), and b) the distance between the corner marker and short arm marker (SAD). Additionally, the third dependent variable was the angle of the marker configuration.

The markers were left in place for Trial B, and each combination of conditions was revisited. The cameras were set up in a circular pattern around an 18’x18’ room and sit 12 feet above the ground mounted on concrete walls. The angles between them are approximately 53.2°, 39.9°, 23.7°, 32.1°, 48.7°, 51.9°, 28.3°, and 34.7° respectively. For each combination of marker size and sample rate, 10 data sets were collected. Each trial was 3 seconds in duration.

Precision was measured by collecting data on a different session (Trial C). The carpenter square with the .5-inch markers (Carpenter Square 1) was utilized and the markers were kept in the same location for the precision trials. A separate carpenter square was utilized for the .75-inch markers (Carpenter Square 3) and had different distance measurements than the repeatability large marker carpenter square (Carpenter Square 2). Data were collected using the same combinations of marker and sample rate conditions as Trials A and B. There were two conditions added to Trial C: (a) Motion (vertical, lateral, and rotation); and (b) Static. Each condition had a mechanical system designed to standardize the respective motion. A rope, pulley, and fixed weight system was used during vertical motion condition. For the side-to-side condition, the carpenter square was fixed to paracord between two pulleys (#KT3049 Big Jon Sports, Interlochen, MI) that was moved by the same rope, pulley, and fixed weight system. A custom designed rotational device was used to administer the rotation motion for each trial. The motion of the rotational device was standardized utilizing the rope, pulley and fixed weight system. This reduced the introduction of human error during the rotational motion conditions.

Data Analysis

Repeatability was assessed using a *t*-test to compare the angle and distance measurements of the 20 trials from session A and the 20 trials from session B. The distances evaluated included a) the distance between the corner marker and long arm marker, and b) the distance between the corner marker and short arm marker. To display the stability of the repeated results, the standard deviation was also reported.

Precision was assessed for each condition utilizing a multivariate analysis of variance (MANOVA). The dependent variables were differences of distance and angle (three dependent variables total). Each MANOVA had four levels, 2 factors for size and 2 factors for speed (2 x 2 multivariate analysis). It is multivariate because all three dependent variables were included into one analysis. To determine the actual distance between markers, pins were placed in the center of each marker and measured with a measuring tape to the nearest millimeter. To determine actual angle measurements of the markers, The Law of Cosines was used by utilizing the measured distances between the markers (Leff, 2005).

$$c^2 = a^2 + b^2 - (2ab)(\cos C) \tag{1}$$

Results

Repeatability

For both length and angle, no significant differences were found between Trial A and Trial B (LAD: $t(38) = 1.229$, $p = .226$; SAD: $t(38) = 1.006$, $p = .321$; Angle: $t(38) = .369$, $p = .714$), as shown in Table 1. Further, the standard deviations for each dependent variable (LAD, SAD, and Angle) were .0029mm, .0024mm, .1488mm respectively. This is further depicted in Figure 2 and Table 2.

Precision

The precision of each dependent variable was affected by specific combination of conditions that were present in the study. As shown in Table 3, the results of the lateral condition showed that speed (i.e., sample rate) alone does not make a significant difference on the measurement of LAD, SAD or Angle. However, we did find that marker size alone does make a significant difference in the LAD (p = .001) and Angle (p = .000) measurements. Further, the combination of sample rate and size makes a significant difference only in the LAD (p = .000) measurement.

Table 4 shows that the vertical condition heeded different results. Sample rate (Hz) alone makes a significant difference in both length measurements, LAD (p = .000) and SAD (p = .005). Further, the size of the marker creates a significant difference in all dependent variables, LAD (p = .000), SAD (p = .000), and Angle (p = .011). Lastly, the interaction between maker size and speed of the sample rate creates a significant difference in the SAD (p = .000) and Angle (p = .001) measurements.

For the rotation condition, the ANOVA found that sample rate (Hz) makes a significant difference in SAD (p = .036) and Angle (p = .000) measurements only. Additionally, size alone creates a significant difference in all dependent variables, SAD (p = .000), LAD (p = .000), and Angle (p = .000). The interaction between marker size and sample rate conditions also creates a significant difference in the measurements of all dependent variables (p = .000 for all variables). These results are shown in Table 5.

Table 6 shows the ANOVA results for the static condition where sample rate (Hz) alone makes a significant difference in Angle ($p = .024$) only. Further, marker size and the interaction between marker size and sample rate creates a significant difference in both length measurements, LAD ($p = .000$ for both conditions) and SAD ($p = .000$ for both conditions), but not Angle measurement.

For the Vertical condition, Table 7 shows the largest difference between the captured and actual measurements of LAD was 0.09mm with the interaction between the 200Hz sample rate and .75-inch marker. The smallest difference was <0.01mm with the interaction between the 100Hz sample rate and .50-inch marker. For the SAD measurement shown in Table 8, the largest difference between the captured and actual measurements is 0.07mm with the interaction between the 100Hz sample rate and a .50-inch marker. The smallest difference was <0.01mm with the interaction between the 100Hz sample rate and .75-inch marker. Lastly, for the Angle measurement shown in Table 9, the largest difference between captured and actual measurements was 0.16 degrees with the interaction between the 200Hz sample rate and .50-inch marker. The smallest difference was <0.01 degrees with the interaction between the 200Hz sample rate and .75-inch marker.

For the Lateral condition, Table 7 shows the conditions that heeded the largest difference between the captured and actual measurements of LAD is 0.09mm with the interaction between the 100Hz sample rate and .50-inch marker. The smallest difference was 0.03mm with the interaction between the 100Hz sample rate and .75-inch marker. For the SAD measurement shown in Table 8, the largest difference between the captured and actual measurements is 0.09mm achieved with the interactions between 2 different combinations of conditions, a) 200Hz and .50-inch marker, and b) 200Hz and .75-inch marker. The smallest difference was 0.01mm achieved with the interaction between remaining two combinations of conditions, a) 100Hz and .50-inch marker, and b) 100Hz and .75-inch marker. Lastly, for the Angle measurement shown in Table 9, the largest difference between captured and actual measurements was 0.37 degrees with the interaction between the 200Hz sample rate and .50-inch marker. The smallest difference was 0.04 degrees with the interaction between the 100Hz sample rate and .75-inch marker.

For the Rotation condition, Table 7 shows the conditions that heeded the largest difference between the captured and actual measurements of LAD is 0.10mm with the interaction between the 100Hz sample rate and .75-inch marker. The smallest difference was 0.02mm with the interaction between the100Hz sample rate and .50-inch marker. For the SAD measurement shown in Table 8, the largest difference between the captured and actual measurements is 0.10mm with the interaction between the 200Hz sample rate and .50-inch marker. The smallest difference was 0.03mm with the interaction between the 200Hz sample rate and .75-inch marker. Lastly, for the Angle measurement shown in Table 9, the largest difference between captured and actual measurements was 0.21 degrees with the interaction between the 200Hz sample rate and .50-inch marker. The smallest difference was 0.099 degrees with the interaction between the 100Hz sample rate and .75-inch marker.

For the Static condition, Table 7 shows the condition that resulted in the largest difference between the captured and actual measurements of LAD was the interaction between the 200Hz sample rate and .75-inch marker at 0.17mm. The smallest difference was 0.04mm with the interaction between the 200Hz sample rate and .50-inch marker. For the SAD measurement shown in Table 8, the largest difference between the captured and actual measurements is 0.13mm with the interaction between the 200Hz sample rate and .75-inch marker. The smallest difference was 0.04mm with the interaction between the 200Hz sample rate and .50-inch marker. Lastly, for the Angle measurement shown in Table 9, the largest difference between captured and actual measurements was 0.34 degrees with the interaction between the 100Hz sample rate and .50-inch marker. The smallest difference was 0.05 degrees with the interaction between the 100Hz sample rate and .75-inch marker.

The summary of the means and standard deviations of each condition for the LAD measurement is outlined in Table 7. For the LAD measurement, the largest *SD* for the vertical, lateral, and rotation conditions were 0.1134mm, 0.00086mm, and 0.00058mm, respectively (see Figure 3 and Figure 4). The static condition heeded similar results, the largest *SD* of the LAD measurement was 0.00051 (see Figure 5 and Figure 6).

The summary of the means and standard deviations for the SAD measurement is outlined in table 8. The standard deviations for the SAD measurement were slightly smaller with the .5-inch markers in the vertical, lateral, and rotation conditions (see Figure 7 and Figure 8). The static condition, however, heeded results that were almost identical, the largest *SD* found with the 200Hz, .75-inch marker interaction (see Figure 9 and Figure 10).

The means and standard deviations were larger in all conditions when the angle measurement was analyzed (Table 9). Again, the standard deviations for the angle measurements were slightly smaller with the .5-inch marker in the vertical, lateral, and rotation conditions (see Figure 11 and Figure 12). The largest standard deviation seen in the static condition was 0.09 and is depicted in Figure 13. Further graphic depictions of the static condition means and standard deviations for angle measurement can be seen in Figure 14.

Discussion

The precision and repeatability of the Motion Analysis Corporation Digital motion capture system was examined in this investigation. The first hypothesis addressed the precision of the motion capture system and whether there would be a significant difference between captured position and angle and actual position and angle of each marker size at each sample rate. We hypothesized there would be no significant differences, and the results were mixed. We found that certain interactions between conditions created a significant difference between precision measurements for the lateral, rotation, vertical, and static conditions.

The most consistent variable that heeded significant results was the size of the marker. Marker size created a significant difference in all measurements (distance and angle) in the rotation and vertical conditions, in LAD and SAD measurements in the static condition, and in LAD and angle measurements in the lateral condition. There are a few ways to interpret these results. The larger markers have more surface area and therefore more reflective tape. This could allow the cameras more opportunity to pick up the reflection from the larger markers. Conversely, the smaller markers covered less space on the carpenter square and require the cameras to pick up the reflection from a more exact area. This could possibly lead to higher precision in measurement because of the diameter of the smaller markers. The cameras can detect the marker from any point on its reflective surface. Theoretically, if the diameter of a marker is .5-inches, the motion capture system has to coordinate with information from each camera to determine the location of the marker with more precision than if the diameter of a marker is larger, or .75-inches. For instance, camera 1 could detect the larger marker on the top right of the surface while camera 5 may detect the larger marker on the bottom left. That means the system needs to negotiate where the marker is based on the two different detected locations. A smaller marker would allow for a smaller difference in location detection simply due to the smaller diameter of the marker.

The sample rate produced significant results in a handful of conditions as well. The lateral condition was the only condition where the sample rate did not heed significant results. This could be due to the set up of the cameras and the markers only being exposed to 5 of the 8 cameras. However, it could also be associated with the lateral movement of the markers and the lack of location change in the Z and X-axes. This motion capture system may favor movement along the Y-axis and therefore heed more precise results. This can be further be seen in the lack of significance found in the lateral condition during the interaction marker size and sample rate.

The interaction between the marker size and sample rate produced a significant result in at least one measurement (SAD, LAD, or Angle) in each condition. For the lateral condition, the only significant difference was found in the LAD measurement. The largest difference was .09mm and was found with the interaction between the 100Hz sample rate and .5-inch marker. It is important to consider this difference from a clinical perspective to decide of the statistical significance of .09mm constitutes clinical significance as well. The vertical condition produced significant results in the SAD and

Angle measurements. The largest difference in the SAD measurement also came from the interaction between the 100Hz sample rate and .5-inch marker. The angle measurement's largest difference came from a different interaction. The interaction between the 200Hz sample rate and .5-inch marker heeded the largest difference at .16 degrees. Again, it is important to think about the clinical significance of .16 degrees and how that error applies to the context of how the system is being used in the clinic. Interestingly, the rotation condition produced statistically significant results in each measurement, LAD, SAD, and angle. The largest differences found in each of these measurements were .10mm, .10mm, and .21 degrees respectively. The largest differences in SAD and angle measurements were both during the interaction of the 200Hz sample rate and .5-inch marker. For the LAD measurement, the largest difference was found with the interaction between the 100Hz sample rate and .75-inch marker. The rotation condition may have heeded statistically significant differences due to the movement taking place along the X and Y -axes. Every other condition had at least a small amount of movement along each of the X, Y, and Z -axes. The rotation condition is the only scenario where the markers were fixed to a device that could not move up and down along the Z-axis. Another possibility for the significant difference is the speed in which the rotational device was moving. While the rate of speed that the carpenter square was moving for each condition was not measured, it was observed that the rotation condition seemed to be moving the carpenter square at a must faster rate than the lateral and vertical conditions. If the motion capture system has limitations in precision with faster movement speeds, this could account for the differences during the rotation condition. It is important to emphasize, however, that the clinical significance of the findings should be taken into account when determining the appropriateness of the system for a given study.

In the second hypothesis, we were interested in the repeatability of the motion capture system and if a significant difference would be found in 2 separate trials utilizing the same set of conditions. No significant differences were found between Trial A and Trial B for any set of conditions which supported the hypothesis. Examining the repeatability of this motion capture system is important to the fidelity of any research studies utilizing this technology. Accurate repeatability affords relative certainty to researchers that the equipment being utilized will perform the same way each day and each time it is powered on. Ultimately this leads to more reliable research studies.

As stated previously, a comprehensive study on a Motion Analysis Corporation motion capture system has not been completed since 1999 (Richards). The results of this study were similar to that study, but ultimately heeded more precise results. The maximum error in angle measurement in the Richards (1999) study was 6.284 degrees while the maximum error in angle measurement in the present study was .37 degrees. This is further demonstrated in the distance measurements. The Richards (1999) study found a maximum distance measurement error of 1.83mm while the present study found a maximum distance error of .17mm.

While the design of the study was initially modeled after the States and Pappas (2006) study, there were extensive modifications done to the design therefore making it difficult to compare the results directly. When comparing standard deviations in length, States and Pappas (2006) reported an average within-trial SD of .125mm. The current study had more conditions, but of all the conditions, the largest within-trial SD was

0.019mm (lateral condition), indicating more precise measurements than the Optotrak 3020 system they evaluated, this is further depicted in Figure 3 and Figure 4. Their angle measurements, however, had an average within-trial SD of .0196 degrees. This is much lower than the SD of any condition in the present study which can be seen in Figure 5. It is important to note, however, that the conditions tested in both studies were very different and it may not be appropriate to compare the results for either length or angle due to these differences.

Occupational Therapy Implications

As stated previously, the clinical significance of the difference in actual versus captured measurements may not be the same as the statistical significance. When measuring the distance that someone walks, or how far the client's bed is from their commode, .10mm is not large enough to be clinically significant for an occupational therapist. Further, when measuring a patient's shoulder range of motion, .37 degrees will probably not be detectable to the naked eye, nor does it constitute clinically significant change in a client's range of motion. Moreover, the gradations on typical goniometers will not have that level of precision. The most important implications for occupational therapy that this study brings is that human movement, both in distance and angle, can be measured to see clinically relevant change in a client. Utilizing this technology to determine a client's abilities before therapeutic intervention and then after therapeutic intervention will help add to the evidence base of occupational therapy practice. The fact that measurements can be detected on such a precise scale gives greater opportunity for improvement in client's functional movements to be seen.

The most significant limitation to this study was that seven cameras were one model, Owl, and one camera was a different model, Raptor. Shortly after the sponsoring university purchased the eight-camera Owl system, the motion capture company discontinued the model. When one of the cameras reached end of life before the initiation of this study, a replacement of the same model could not be obtained and the university had to purchase a replacement camera in a different model.

Another limitation of the study was that the cameras would periodically "see" markers that were not actually there. This could be due to lighting in the research lab or reflective surfaces of other objects, but it should be considered when evaluating this study. Additionally, when testing the system during the lateral condition, there was some inadvertent movement of the carpenter square along the X-axis, creating movement that was not strictly lateral along the Y-axis. This also happened during the vertical condition testing.

Finally, there were 10 data sets collected for each combination of sample rate and marker size for each condition. To make this study stronger, more trials could have been done for each combination to increase statistical power.

Future Directions

Future research is needed on the Motion Analysis Corporation motion capture system involving all cameras of one model. This would help researchers understand if intermixing camera models affects the outcome of precision and repeatability of the overall system. Further, more studies are needed in comparing systems against each other. It is important for researchers and clinicians to know what systems are the most accurate as well as the accuracy of systems within differing price-points. Technology is constantly and rapidly changing, it is important for researchers to be up to date on the precision and repeatability of the newest motion capture systems, not just systems that are obsolete or out of service.

Conclusion

Overall, the investigators conclude that the results demonstrate that the Motion Analysis Corporation Digital motion capture system is highly precise and repeatable. The most precise measurements resulted from the interaction between the larger marker and slower sample rate, although the results were mixed enough that further studies are needed to determine if this is truly the most precise combination. Further, the investigators determined that the system produced highly repeatable results. Motion capture technology has the potential to significantly change research in occupational therapy; the stronger the research behind the technology, the stronger occupational therapy research will become. Future research should investigate other motion capture systems to ascertain measurement fidelity, particularly for systems used in current occupational therapy research.

Acknowledgements

This research would not have been possible without the assistance of several individuals. I would like to thank my research advisor, Dr. Martin Rice, for his unwavering support and encouragement throughout this process as well as sharing his contagious passion for research with me. Thank you to Megan Blake, Richelle Gray, Jenell Roberts, and Kaitlin Lemon for helping with various aspects of this project including the lab set up and trial execution. I would also like to thank the University of Toledo Occupational Therapy program for providing the lab space and equipment to make this research project possible. Lastly, I would like to thank my family, friends, and classmates for their support along the way; the process was much more enjoyable due to all of you.

References

Allison, T. (2011). More than a Man in a Monkey Suit: Andy Serkis, Motion Capture, and Digital Realism. *Quarterly Review of Film and Video, 28*(4), 325-341.

Bartnik, L., & Rice, M. (2013). Comparison of Caregiver Forces Required for Sliding a Patient Up in Bed Using an Array of Slide Sheets. *Workplace health & safety,* 393-400.

Bregler, C. (2007). Motion capture technology for entertainment [in the spotlight]. *Signal Processing Magazine, IEEE, 24*(6), 160-158.

Carse, B., Meadows, B., Bowers, R., & Rowe, P. (2013). Affordable clinical gait analysis: An assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. *Physiotherapy, 99*(4), 347-351. doi: 10.1016/j.physio.2013.03.001

Chiari, L., Della Croce, U., Leardini, A., & Cappozzo, A. (2005). Human movement analysis using stereophotogrammetry. Part 2: instrumental errors. *Gait Posture, 21*(2), 197-211. doi: 10.1016/j.gaitpost.2004.04.004

Cooper, J., Shwedyk, E., Quanbury, A., Miller, J., & Hildebrand, D. (1993). Elbow joint restriction: effect on functional upper limb motion during performance of three feeding activities. *Archives of physical medicine and rehabilitation, 74*(8), 805-809.

Coutts, F. (1999). Gait analysis in the therapeutic environment. *Manual Therapy*, *4*(1), 2-10.

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575-587.

Durlach, N. I., & Mavor, A. S. (1994). *Virtual reality: scientific and technological challenges*: National Academies Press.

Ewers, R., Schicho, K., Undt, G., Wanschitz, F., Truppe, M., Seemann, R., & Wagner, A. (2005). Basic research and 12 years of clinical experience in computer-assisted navigation technology: a review. *Int J Oral Maxillofac Surg, 34*(1), 1-8. doi: 10.1016/j.ijom.2004.03.018

Feng, C. J., & Mak, A. F. (1997). Three-dimensional motion analysis of the voluntary elbow movement in subjects with spasticity. *Rehabilitation Engineering, IEEE Transactions on, 5*(3), 253-262.

Geroch, M. S. (2004). Motion capture for the rest of us. *Journal of Computing Sciences in Colleges, 19*(3), 157-164.

Gruen, A. (1997). Fundamentals of videogrammetry—a review. *Human Movement Science, 16*(2), 155-187.

Guerra-Filho, G. (2005). Optical Motion Capture: Theory and Implementation. *RITA, 12*(2), 61-90.

Leff, L. S. (2005). *Precalculus the Easy Way*: Barron's.

Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clinical Biomechanics, 14*(9), 612-619.

Nakamura, T., Abreu, B. C., Patterson, R. M., Buford, W. L., & Ottenbacher, K. J. (2008). Upper-limb kinematics of the presumed-to-be-unaffected side after brain injury. *American Journal of Occupational Therapy, 62*(1), 46-50.

Rash, G. S., Belliappa, P. P., Wachowiak, M. P., Somia, N. N., & Gupta, A. (1999). A demonstration of the validity of a 3-D video motion analysis method for measuring finger flexion and extension. *J Biomech, 32*(12), 1337-1341.

Rice, M. S., & Thomas, J. J. (2000). Perceived risk as a constraint on occupational performance during hot and cold water pouring. *The American Journal of Occupational Therapy, 54*(5), 525-532.

Richards, J. G. (1999). The measurement of human motion: A comparison of commercially available systems. *Human Movement Science, 18*(5), 589-602.

Salvi, J., Armangué, X., & Batlle, J. (2002). A comparative review of camera calibrating methods with accuracy evaluation. *Pattern recognition, 35*(7), 1617-1635.

Shurtleff, T. L., Standeven, J. W., & Engsberg, J. R. (2009). Changes in dynamic trunk/head stability and functional reach after hippotherapy. *Archives of physical medicine and rehabilitation, 90*(7), 1185-1195.

States, R. A., & Pappas, E. (2006). Precision and repeatability of the Optotrak 3020 motion measurement system. *J Med Eng Technol, 30*(1), 11-16. doi: 10.1080/03091900512331304556

Tebbutt, P., Wood, J., & King, M. (2002). The Vicon Manual: Oxford: OMG Plc.

Thewlis, D., Bishop, C., Daniell, N., & Paul, G. (2013). Next generation low-cost motion capture systems can provide comparable spatial accuracy to high-end systems. *Journal of Applied Biomechanics*, *29*(1), 112-117.

Trombly, C. A., & Wu, C.-Y. (1999). Effect of rehabilitation tasks on organization of movement after stroke. *The American Journal of Occupational Therapy, 53*(4), 333-344.

Vicon, V. M. (2006). Hardware System Reference, revision 1. *Vicon Motion Systems Limited*.

Welch, G., & Foxlin, E. (2002). Motion tracking: No silver bullet, but a respectable arsenal. *Computer Graphics and Applications, IEEE, 22*(6), 24-38.

Wiles, A. D., Thompson, D. G., & Frantz, D. D. (2004). *Accuracy assessment and interpretation for optical tracking systems.* Paper presented at the Medical Imaging 2004.

Wu, C.-y., Chen, C.-l., Tang, S. F., Lin, K.-c., & Huang, Y.-y. (2007). Kinematic and clinical analyses of upper-extremity movements after constraint-induced movement therapy in patients with stroke: a randomized controlled trial. *Archives of physical medicine and rehabilitation, 88*(8), 964-970.

Table 1.

Summary of the Paired Samples Means (mm) and SD (mm) of Trial A[a] and Trial B for all Conditions to test Repeatability

	Trial A[b]		Trial B[b]	
Condition	*M*	*SD*	*M*	*SD*
Mean LAD	49.85	.0029151	49.84	.0030455
Mean SAD	30.13	.0023862	30.12	.0031392
Mean Angle	89.84	.1487739	89.82	.5141859

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Trial A and Trial B were conducted 1 week apart with identical conditions to test repeatability; Trial A was first and Trial B was second.
[b] n=39 – add to table, take out of notes
*p < .05

Table 2.

Summary of the Paired Samples Test of the Repeatability Trials A[a] and B for all Conditions to Test Repeatability of the System.

Paired Condition	*t*	*df*	*p*-value[b]
Mean LAD A-Mean LAD B	1.229	38	.226
Mean SAD A-Mean SAD B	1.006	38	.321
Mean Angle A-Mean Angle B	.369	38	.714

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Trial A and Trial B were conducted 1 week apart with identical conditions to test repeatability; Trial A was first and Trial B was second.
[b]2-tailed
*$p < .05$

Table 3.

Multivariate Analysis of Variance Tests of Between-Subjects Effects for Lateral Condition

Source	Dependent Variable	Type III *SS*	*df*	*MS*	*F*	*p*-value
Hz	LAD Difference	0.000000112	1	0.000000112	2.76	.106
	SAD Difference	0.000005941	1	0.000005941	2.75	.106
	Angle Difference	0.018	1	.018	1.41	.242
Size[a]	LAD Difference	0.000000577	1	0.000000577	14.24	.001*
	SAD Difference	0.000000093	1	0.000000093	.04	.837
	Angle Difference	0.774	1	.774	61.44	.000*
Hz * Size	LAD Difference	0.000001002	1	0.000001002	24.72	.000*
	SAD Difference	0.000000040	1	0.000000040	.02	.892
	Angle Difference	0.004	1	.004	.34	.566
Error	LAD Difference	0.00000146	36	0.000000041		
	SAD Difference	0.0000778	36	0.000002161		
	Angle Difference	0.454	36	.013		
Total	LAD Difference	0.00001639	40			

SAD Difference	0.00009707	40
Angle Difference	3.225	40

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Size of marker
*$p < .05$

Table 4.

Multivariate Analysis of Variance Tests of Between-Subjects Effects for Vertical Condition

Source	Dependent Variable	Type III *SS*	*df*	*MS*	*F*	*p*-value
Hz	LAD Difference	0.00000079	1	0.00000079	41.06	.000*
	SAD Difference	0.00000030	1	0.00000030	9.16	.005*
	Angle Difference	0.00004797	1	0.00004797	.02	.890
Size[a]	LAD Difference	0.00000118	1	0.00000118	61.20	.000*
	SAD Difference	0.00000064	1	0.00000064	19.35	.000*
	Angle Difference	0.018	1	0.018	7.12	.011*
Hz * Size	LAD Difference	0.00000004	1	0.00000004	2.01	.165
	SAD Difference	0.00000147	1	0.00000147	44.42	.000*
	Angle Difference	0.029	1	0.029	11.92	.001*
Error	LAD Difference	0.00000069	36			
	SAD Difference	0.00000119	36			
	Angle Difference	0.089	36			
Total	LAD Difference	0.00001299	40			

SAD Difference	0.00000752	40
Angle Difference	0.637	40

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Size of marker
*$p < .05$

Table 5.

Multivariate Analysis of Variance Tests of Between-Subjects Effects for Rotation Condition

Source	Dependent Variable	Type III *SS*	*df*	*MS*	*F*	*p*-value
Hz	LAD Difference	0.00000000	1	0.00000000	.61	.442
	SAD Difference	0.00000002	1	0.00000002	4.74	.036*
	Angle Difference	0.013	1	0.013	100.54	.000*
Size[a]	LAD Difference	0.00000301	1	0.00000301	619.58	.000*
	SAD Difference	0.00000347	1	0.00000347	736.44	.000*
	Angle Difference	0.274	1	0.274	2039.31	.000*
Hz * Size	LAD Difference	0.00000071	1	0.00000071	145.09	.000*
	SAD Difference	0.00000026	1	0.00000026	55.53	.000*
	Angle Difference	0.001	1	0.001	9.03	.005*
Error	LAD Difference	0.00000018	36	0.00000001		
	SAD Difference	0.00000017	36	0.00000001		
	Angle Difference	0.005	36	0.000		
Total	LAD Difference	0.00001972	40			

SAD Difference	0.0000225	40
Angle Difference	0.810	40

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Size of marker
*$p < .05$

Table 6.

Multivariate Analysis of Variance Tests of Between-Subjects Effects for Static Condition

Source	Dependent Variable	Type III *SS*	*df*	*MS*	*F*	*p*-value
Hz	LAD Difference	0.00000004	1	0.00000004	1.15	.286
	SAD Difference	0.00000028	1	0.00000028	1.67	.200
	Angle Difference	0.116	1	0.116	5.29	.024*
Size[a]	LAD Difference	0.00001636	1	0.00001636	527.56	.000*
	SAD Difference	0.00000379	1	0.00000379	22.34	.000*
	Angle Difference	0.032	1	0.032	1.44	.234
Hz * Size	LAD Difference	0.00000392	1	0.00000392	126.29	.000*
	SAD Difference	0.00000359	1	0.00000359	21.18	.000*
	Angle Difference	0.033	1	0.033	1.49	.226
Error	LAD Difference	0.00000233	75	0.00000003		
	SAD Difference	0.00001271	75	0.00000017		
	Angle Difference	1.644	75	0.022		
Total	LAD Difference	0.000092	79			

SAD Difference	0.00006938	79
Angle Difference	5.977	79

Note. LAD = Distance between corner marker and long arm marker; SAD = Distance between corner marker and short arm marker
[a]Size of marker
*$p < .05$

Table 7.

Summary of the Means, Standard Deviations, and Differences in Captured Distance (mm) Versus Actual Distance between Corner and Long Arm Marker in All Conditions

Condition	*n*	*M*	*SD*	Actual	Difference
Vertical					
S/S	10	50.1	0.00112	50.1	0.00
L/S	10	52.1	0.00054	52.2	-0.05
S/F	10	50.1	0.00134	50.1	-0.04
L/F	10	52.1	0.00052	52.2	-0.09
Lateral					
S/S	10	50.2	0.00076	50.1	0.09
L/S	10	52.2	0.00058	52.2	-0.03
S/F	10	50.1	0.00086	50.1	0.05
L/F	10	52.1	0.00071	52.2	-0.06
Rotation					
S/S	10	50.1	0.00052	50.1	0.02
L/S	10	52.1	0.00052	52.2	-0.10

S/F	10	50.1	0.00058	50.1	0.05
L/F	10	52.1	0.00045	52.2	-0.08
Static					
S/S	20	50.1	0.00004	50.1	0.05
L/S	20	49.6	0.00008	49.7	-0.09
S/F	20	50.1	0.00012	50.1	0.04
L/F	20	49.5	0.00051	49.7	-0.17

Note. S/S = .5-inch marker and 100Hz combination; L/S = .75-inch marker and 100Hz combination; S/F = .5-inch marker and 200Hz combination; L/F = .75-inch marker and 200Hz combination.

Table 8.

Summary of the Means, Standard Deviations, and Differences in Captured Distance (mm) Versus Actual Distance between Corner and Short Arm Marker in All Conditions

Condition	*n*	*M*	*SD*	Actual	Difference
Vertical					
S/S	10	30.4	0.0011	30.3	0.07
L/S	10	29.8	0.0007	29.8	0.00
S/F	10	30.3	0.0017	30.3	-0.01
L/F	10	29.8	0.0008	29.8	-0.03
Lateral					
S/S	10	30.3	0.0014	30.3	-0.01
L/S	10	29.8	0.0007	29.8	-0.01
S/F	10	30.4	0.0190	30.3	0.09
L/F	10	29.7	0.0008	29.8	-0.09
Rotation					
S/S	10	30.4	0.0005	30.3	0.09
L/S	10	29.8	0.0005	29.8	-0.05

S/F	10	30.4	0.0006	30.3	0.10
L/F	10	29.8	0.0005	29.8	-0.03
Static					
S/S	20	30.4	0.0002	30.3	0.10
L/S	20	29.9	0.0001	29.8	0.07
S/F	20	30.3	0.0001	30.3	0.04
L/F	20	29.9	0.0001	29.8	0.13

Note. S/S = .5-inch marker and 100Hz combination; L/S = .75-inch marker and 100Hz combination; S/F = .5-inch marker and 200Hz combination; L/F = .75-inch marker and 200Hz combination.

Table 9.

Summary of the Means, Standard Deviations, and Differences in Captured Angle Versus Actual Angle in All Conditions

Condition	*n*	*M*	*SD*	Actual[a]	Difference
Vertical					
S/S	10	89.55	0.21	89.45	0.10
L/S	10	89.86	0.16	89.98	-0.12
S/F	10	89.61	0.32	89.45	0.16
L/F	10	89.98	0.24	89.98	0.00
Lateral					
S/S	10	89.80	0.20	89.45	0.35
L/S	10	89.94	0.16	89.98	-0.04
S/F	10	89.82	0.18	89.45	0.37
L/F	10	90.09	0.18	89.98	0.11
Rotation					
S/S	10	89.63	0.11	89.45	0.18
L/S	10	89.98	0.10	89.98	0.00

S/F	10	89.66	0.12	89.45	0.21
L/F	10	90.03	0.10	89.98	0.05
Static					
S/S	20	89.79	0.02	89.45	0.34
L/S	20	89.94	0.02	89.89	0.05
S/F	20	89.63	0.02	89.45	0.18
L/F	20	90.01	0.09	89.89	0.12

Note. S/S = .5-inch marker and 100Hz combination; L/S = .75-inch marker and 100Hz combination; S/F = .5-inch marker and 200Hz combination; L/F = .75-inch marker and 200Hz combination.
[a]Actual angle measurement determined by Law of Cosines.

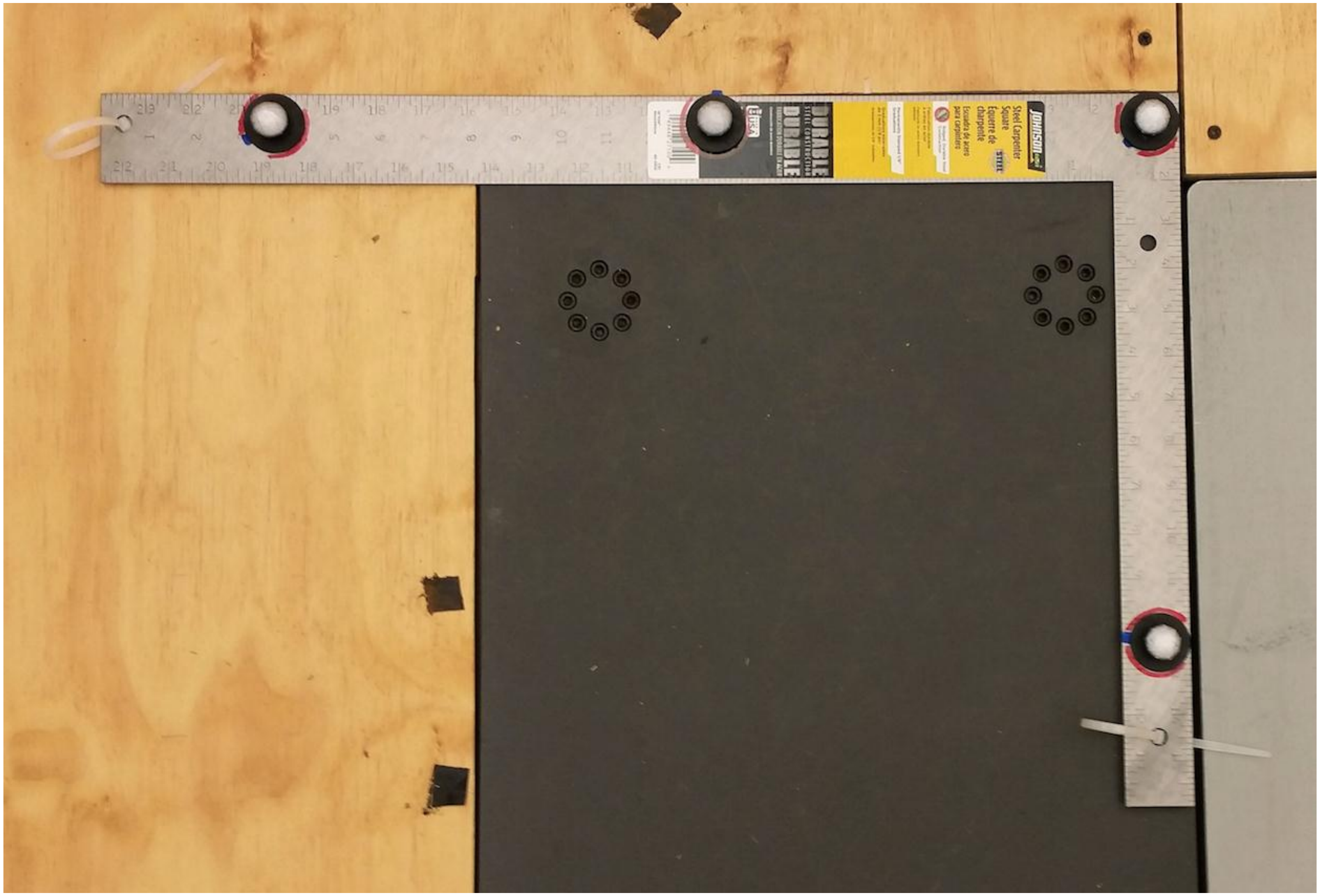

Figure 1. Photograph of marker locations on Carpenter Square #2.

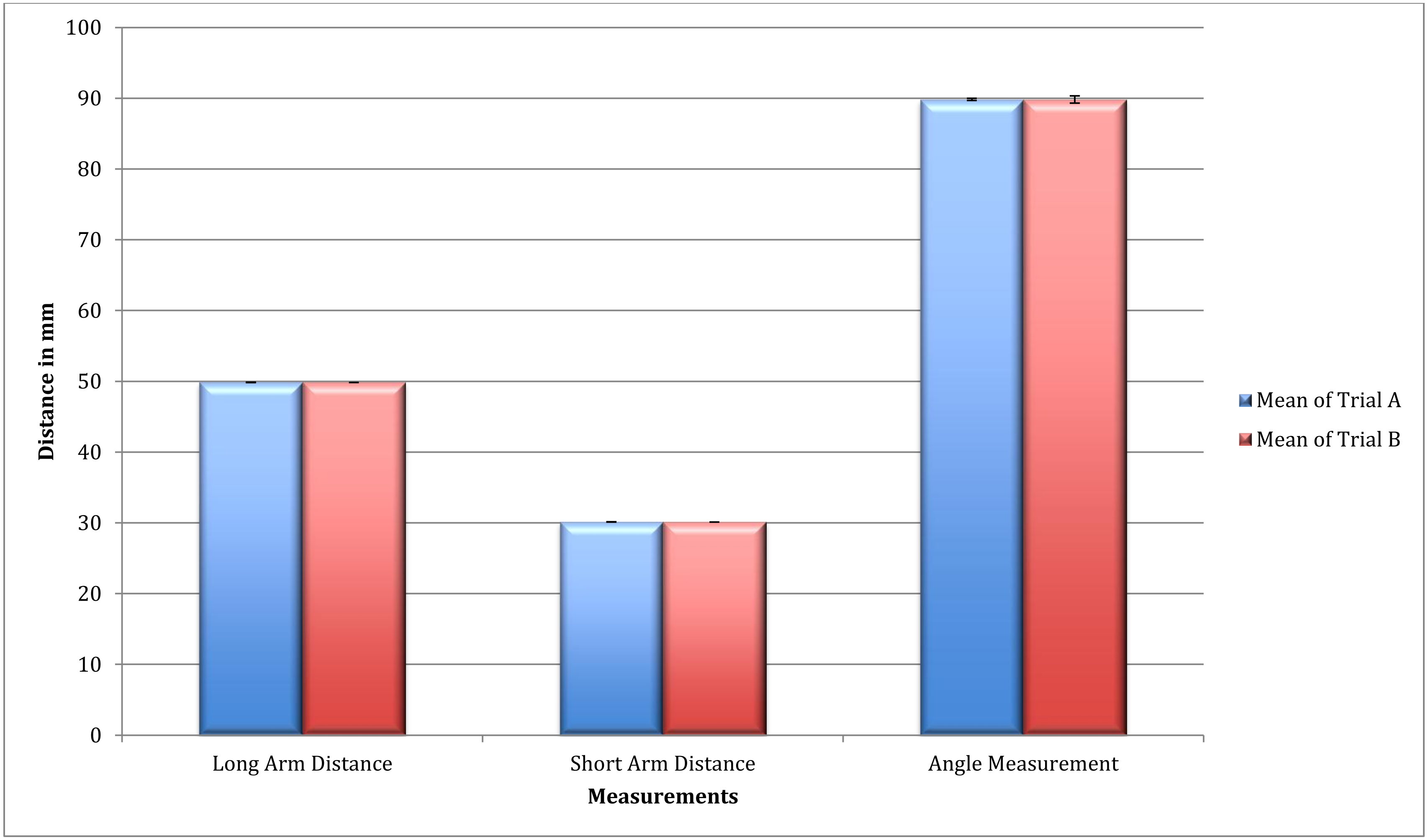

Figure 2. Means and standard deviations in Trial A and Trial B for distance between corner marker and long arm marker, distance between corner marker and short arm marker, and angle measurement. Trial A occurred first and Trial B occurred one week later under the exact same conditions.

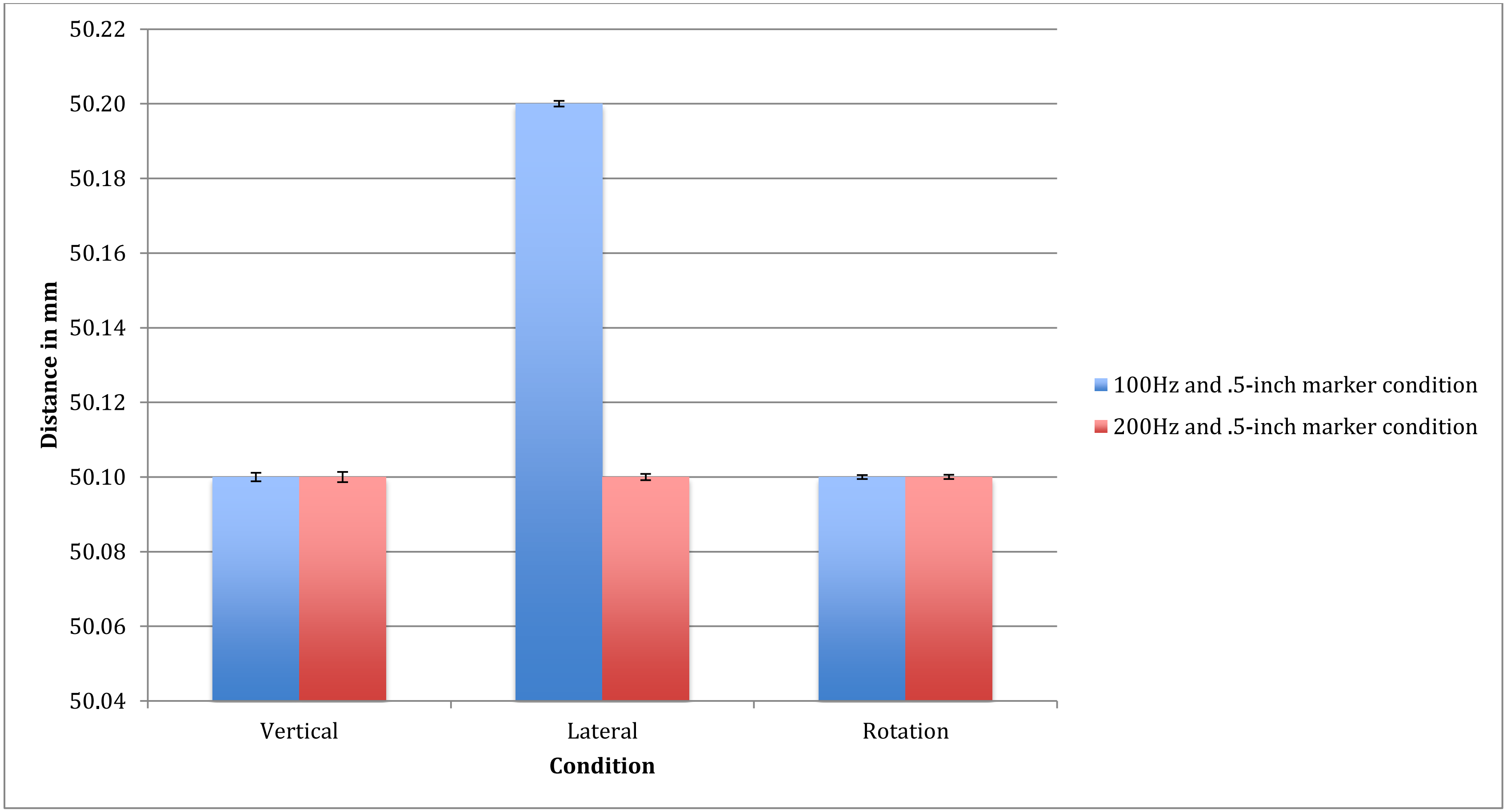

Figure 3. Bar graph showing the mean distances from corner to long end (LAD) of Carpenter Square #1 and standard deviation for each combination of conditions. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.

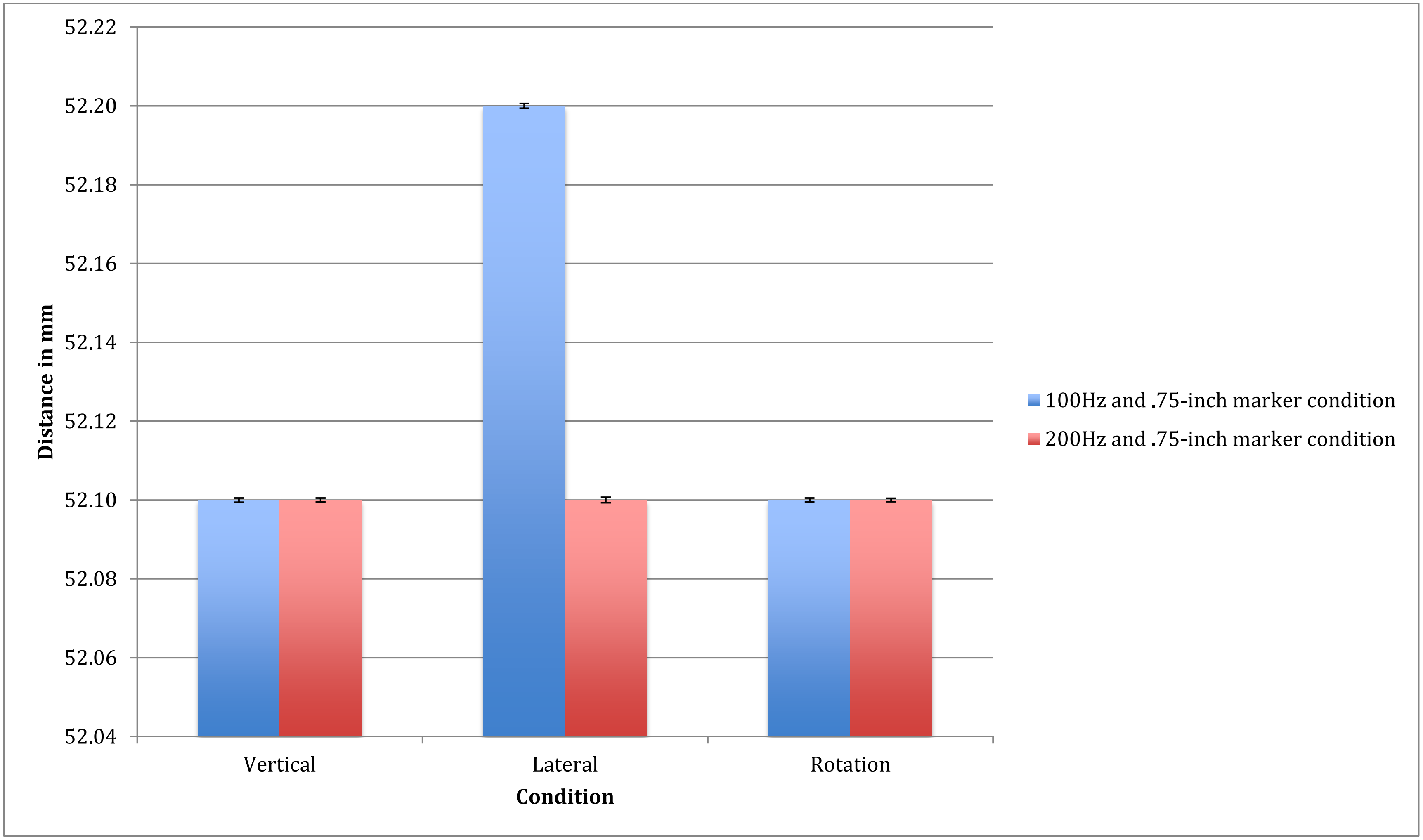

Figure 4. Bar graph showing the mean distances from corner to long end (LAD) of the Carpenter Square #3 and standard deviation for the vertical, lateral, and rotation conditions. Carpenter Square #3 is used only for .75-inch marker precision trials for the vertical, lateral, and rotation conditions.

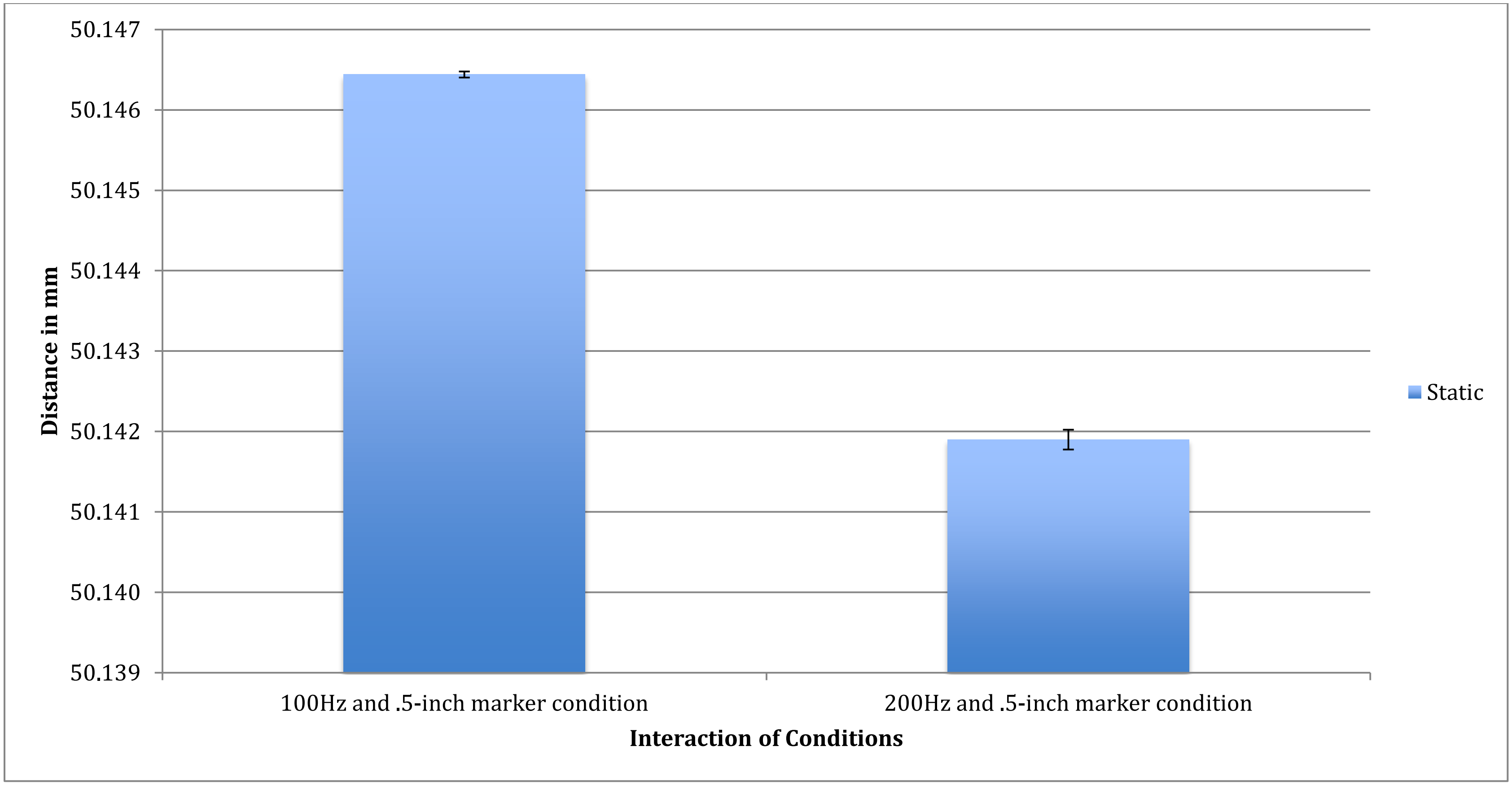

Figure 5. Bar graph showing the mean distances from corner to long end (LAD) of the Carpenter Square #1 and standard deviation for the static condition. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.

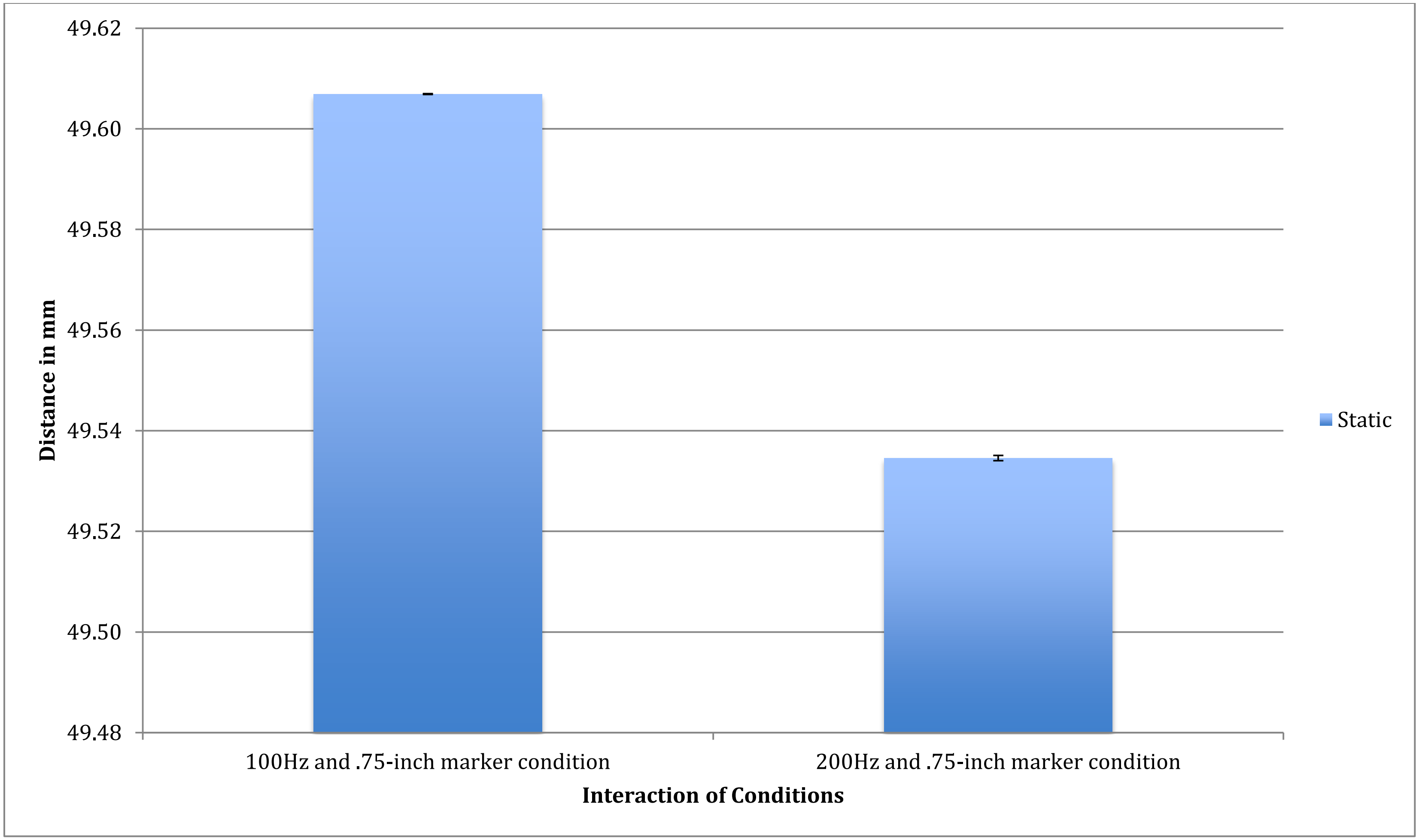

Figure 6. Bar graph showing the mean distances from corner to long end (LAD) of the Carpenter Square #2 and standard deviation for the static condition. Carpenter Square #2 is used for the .75-inch marker repeatability trials and .75-inch marker static precision trials.

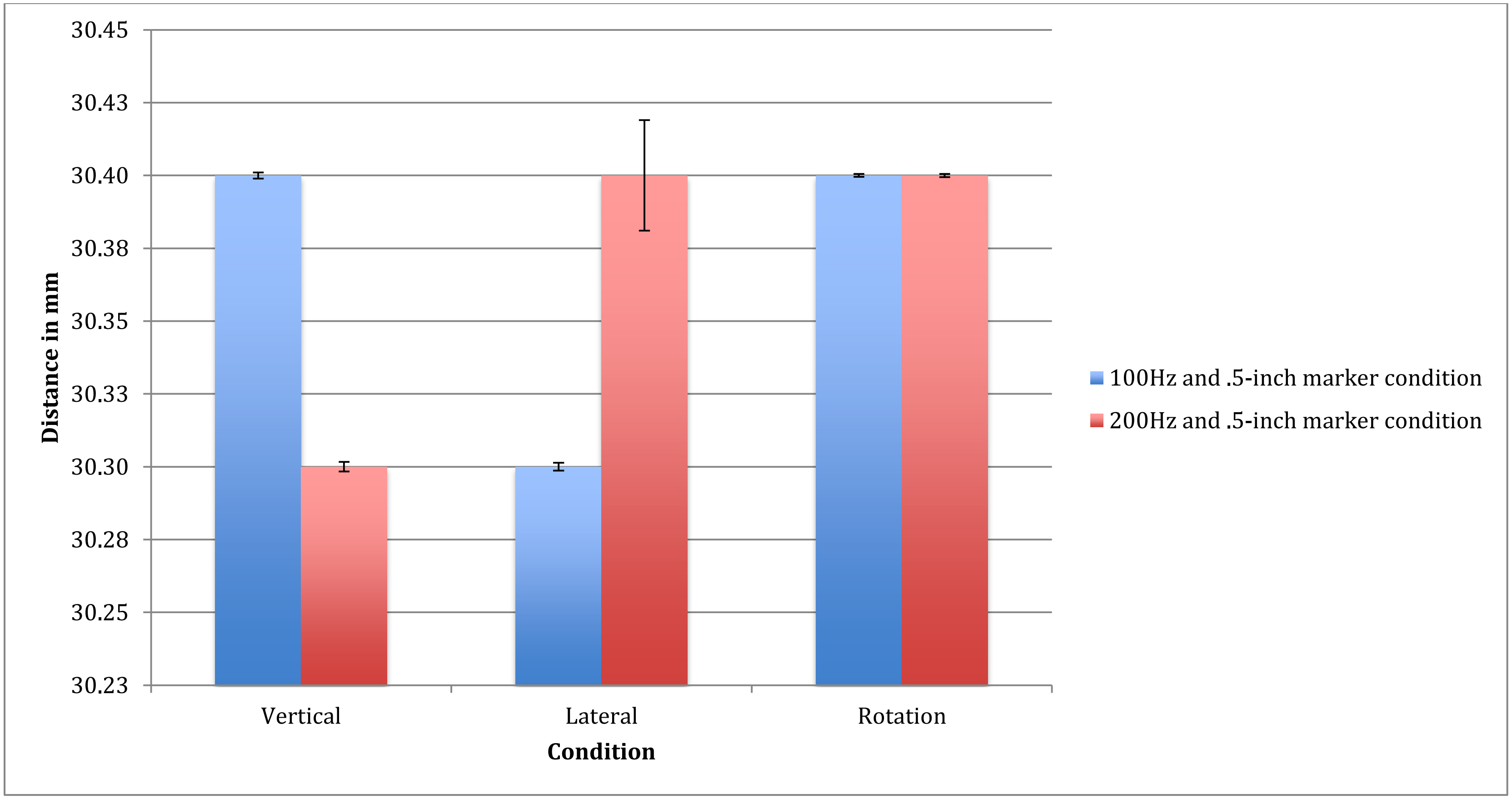

Figure 7. Bar graph showing the mean distances from corner to short end (SAD) of Carpenter Square #1 and standard deviation for the vertical, lateral, and rotation conditions. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.

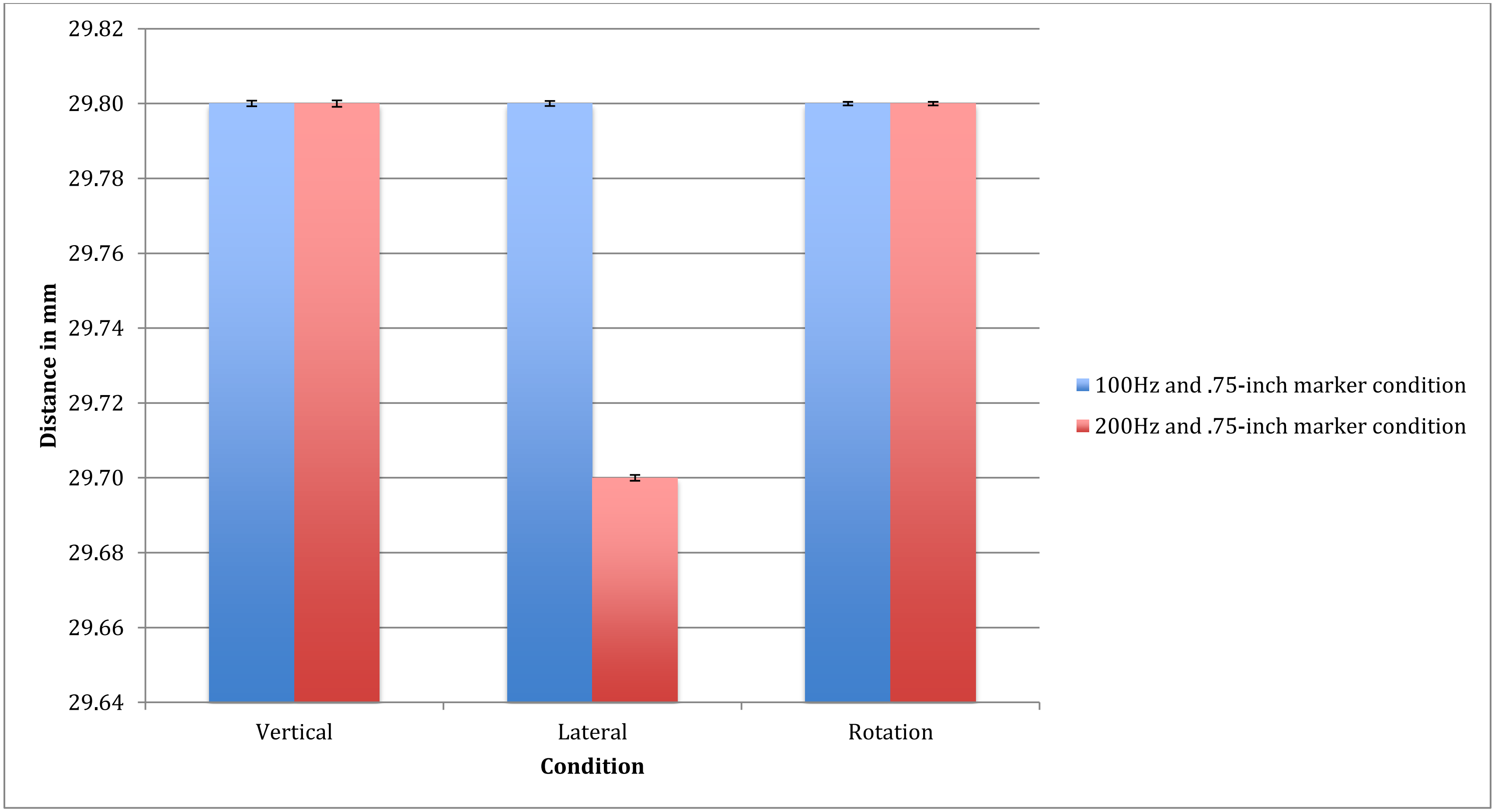

Figure 8. Bar graph showing the mean distances from corner to short end (SAD) of Carpenter Square #3 and standard deviation for the vertical, lateral, and rotation conditions. Carpenter Square #3 is used only for .75-inch marker precision trials for the vertical, lateral, and rotation conditions.

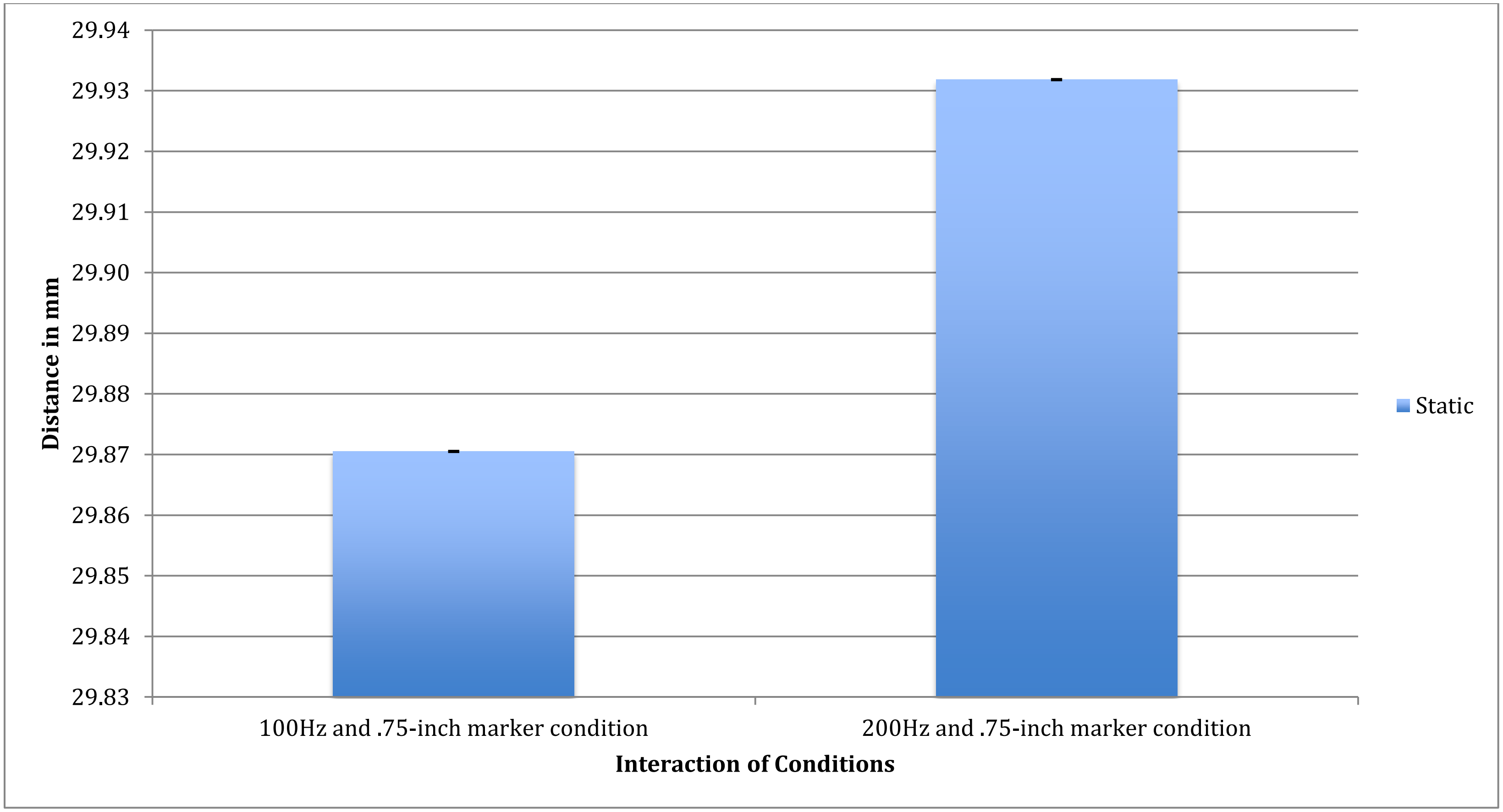

Figure 9. Bar graph showing the mean distances from corner to short end (SAD) of the Carpenter Square #2 and standard deviation for the static condition. Carpenter Square #2 is used for the .75-inch marker repeatability trials and .75-inch marker static precision trials.

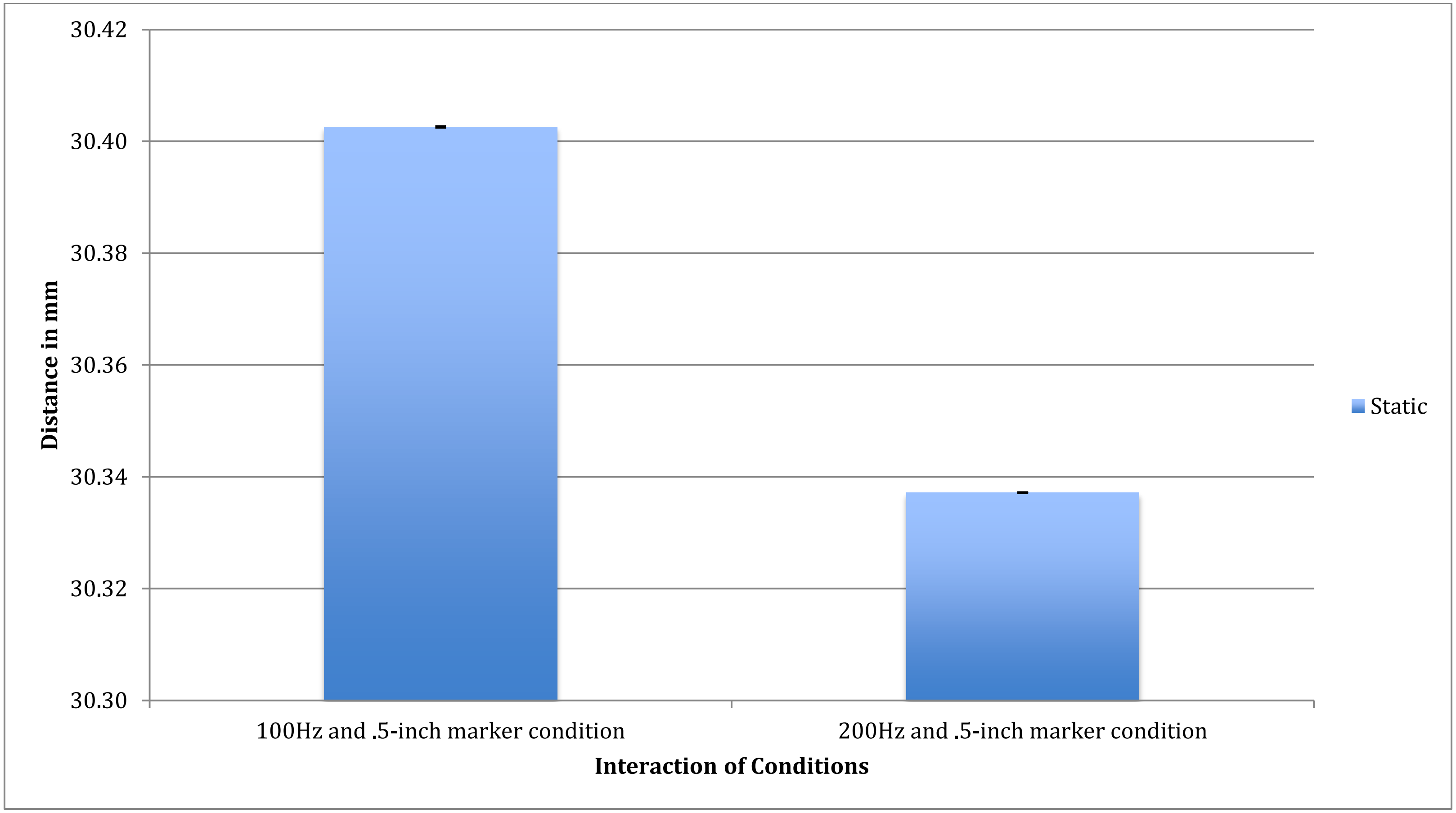

Figure 10. Bar graph showing the mean distances from corner to short end (SAD) of the Carpenter Square #1 and standard deviation for the static condition. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.

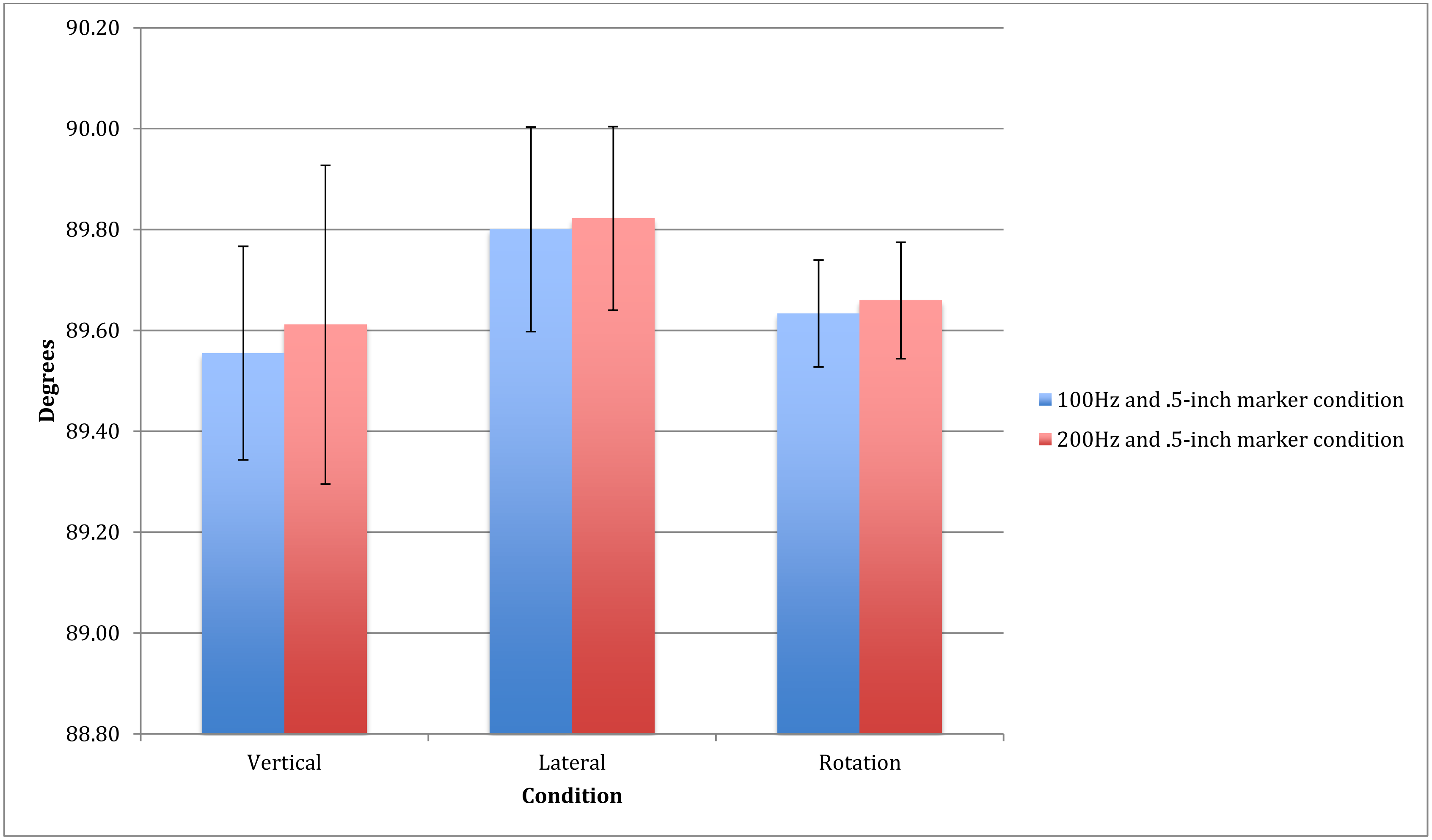

Figure 11. Mean angle and standard deviation for the vertical, lateral, and rotation conditions for Carpenter Square #1. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.

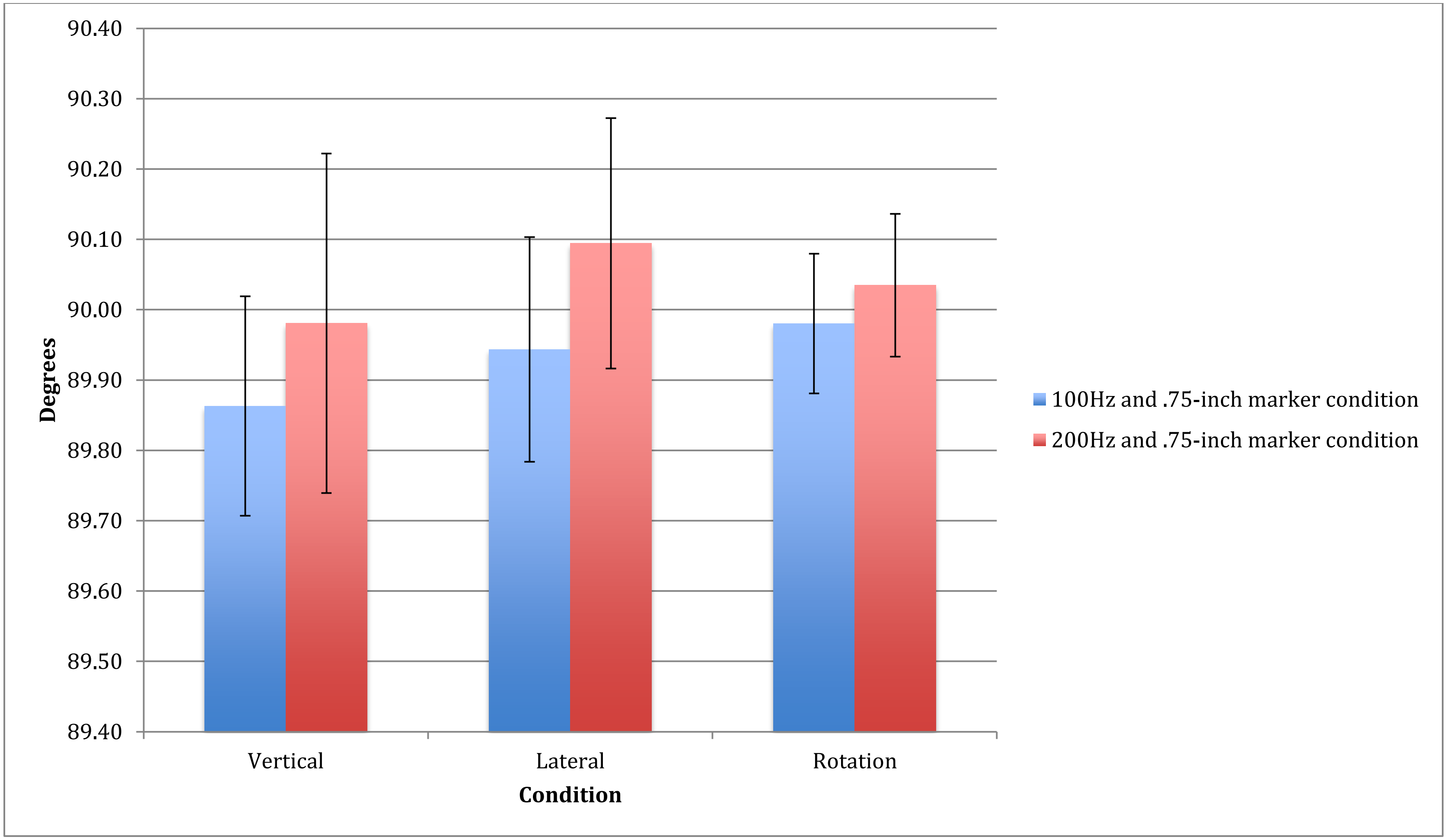

Figure 12. Mean angle and standard deviation for the vertical, lateral, and rotation conditions for Carpenter Square #3. Carpenter Square #3 is used only for .75-inch marker precision trials for the vertical, lateral, and rotation conditions.

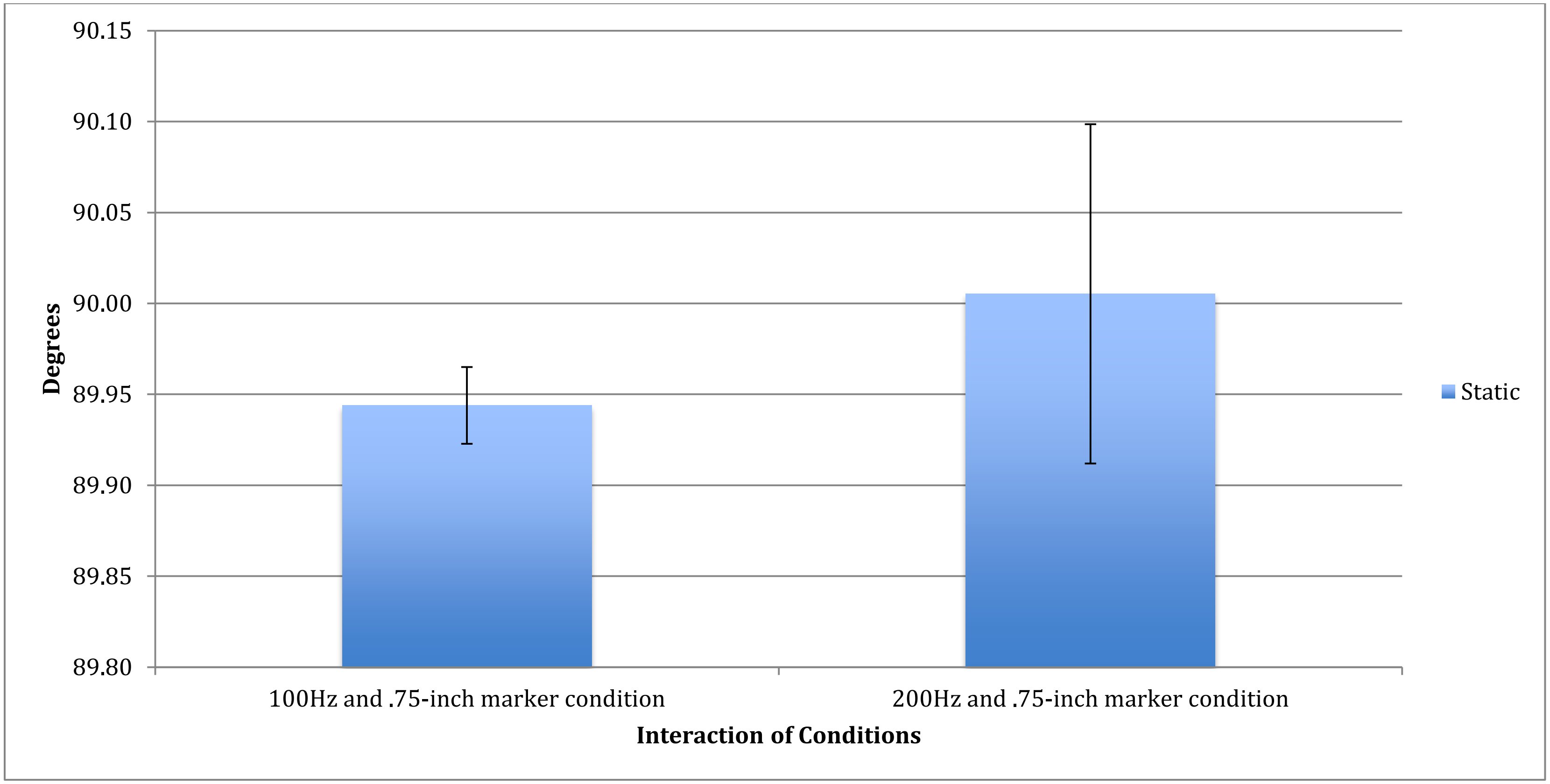

Figure 13. Mean angle and standard deviation for the static condition for Carpenter Square #2. Carpenter Square #2 is used for the .75-inch marker repeatability trials and .75-inch marker static precision trials.

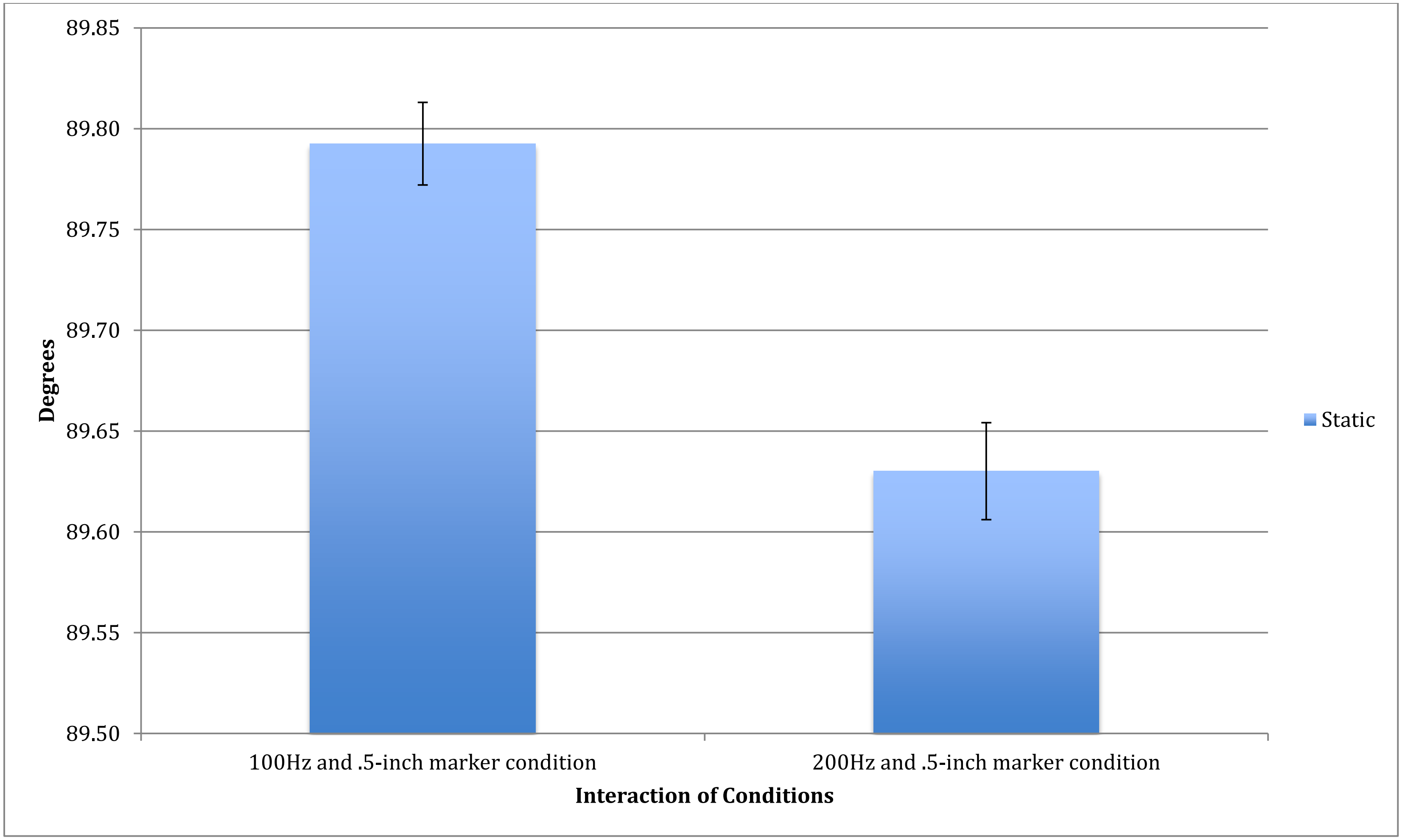

Figure 14. Mean angle and standard deviation for the static condition for Carpenter Square #1. Carpenter Square #1 is used for both the .5-inch marker precision trials and the .5-inch marker repeatability trials.