**Development of a Haptic Pen Hand Precision Circle-Tracing Assessment: Implementing Dynamic Resistive Forces**

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**Abstract**

Hand precision biomechanical assessments are being developed to help improve the ability to diagnose and monitor hand health in clinical/rehabilitation settings. For this study, we developed a circle-tracing assessment using a haptic pen. The objectives were to determine if 1) introducing resistive forces (to the haptic pen) significantly altered tracing accuracy, 2) bilateral differences exist between dominant and non-dominant hands, 3) if patients improved across repeated trials (learning), and 4) if quadrant-specific performance patterns exist during circle tracing.

The participants were 20 healthy university students (11 male, 9 female; 22.3 ± 2.8 years). Circles were traced (on a computer monitor) using a 3D Systems Touch X haptic pen. Five consecutive repetitions were completed for each force level (0.0N, 0.5N, 1.2N) across handedness conditions and rotation directions. Error scores were calculated at each degree around the circle and averaged.

For resistive forces, error scores were lowest for the moderate force (0.5N) condition (18.4% lower than no force, p < 0.001). For handedness, the dominant hand was significantly more accurate than the non-dominant hand (error scores reduced by 1.69mm, p<0.001). For learning, accuracy improved significantly across trials (p<0.001) with a 19.7% improvement from first to last attempt. For quadrant analysis, superior-medial movements demonstrated highest accuracy while inferior-medial movements showed poorest performance (p < 0.001). Significant interactions were found between handedness and rotation direction (p < 0.001), suggesting biomechanical advantages for natural movement patterns.

**Conclusions**: We introduced relatively subtle haptic pen resistive forces, and it impacted tracing accuracy substantially. Consequently, this must be accounted for when developing clinical assessments. Further, clinicians and researchers should be aware that patients had far better accuracy for the dominant hand. Last, there was strong evidence for learning, which suggests a familiarization protocol would be needed before clinical assessments are completed.

**Keywords**: haptic feedback, clinical assessment, hand rehabilitation, force threshold, handedness, circle tracing

**Clinical Messages**

* **Force Impact Accuracy**: Error scores were lowest when the pen had moderate resistive forces (0.5N) (18.4% less). It is unclear why participants did best with moderate forces.
* **Bilateral Assessment Standards**: Dominant hand had consistently superior performance (1.69mm better accuracy), providing clinicians and researchers with baseline expectations
* **Learning Detection**: Tracing accuracy improved substantially within this first session (19.7% improvement across trials). This suggests a familiarization session may be needed before taking clinical assessments.
* **Clinical Implementation**: The assessment protocol demonstrates excellent tolerability as all participants were able to complete the 30 repetitions (with no adverse events)

**Introduction**

With recent advances in technology, biomechanists and engineers have been developing more advanced hand precision assessments to assess hand health in clinical settings. Kinematic examples include electronic handwriting tasks that measure pen pressure, velocity, and trajectory during writing exercises to assess fine motor control and coordination deficits in neurological populations (Rosenblum et al., 2003). Kinetic examples include finger lifting with biofeedback systems that measure maximum voluntary contraction and force control during isolated finger movements (Sisto et al., 2001), pinching precision tasks that assess grip strength and coordination between thumb and fingers using force transducers (Mathiowetz et al., 1985), and finger grasping assessments that evaluate power grip strength and manipulation skills during functional object handling tasks (Westling & Johansson, 1984).

These new hand precision assessments have potential to greatly advance current clinical assessments. The most widely used clinical assessment, the Jebsen Hand Function Test, was developed in 1969. This test consists of seven timed subtasks including writing, card turning, small object manipulation, simulated feeding, stacking, and moving large objects to assess functional hand abilities. A major limitation is the assessment only assesses completion time, providing no direct measures of movement quality. Consequently, this approach provides limited information for the clinicians. In contrast, biomechanical assessments can provide direct and detailed assessments for controlled and relevant tasks (pinching, drawing, etc.). This approach has great potential to identify movement deficits and to detect subtle improvements with rehabilitation.

In this study we focus on developing a hand precision assessment with haptic pen technology. Haptic technology provides tactile feedback through programmable forces, vibrations, or motions that users can feel through specialized devices. The haptic pen used in this study employs force feedback mechanisms that can apply controlled resistance in three-dimensional space, allowing precise measurement of hand position and movement while simultaneously providing variable resistance forces. The haptic pen has many applications including surgical simulation training where medical students practice procedures with realistic force feedback (Coles et al., 2011), rehabilitation robotics for stroke recovery (Krebs et al., 2003), and engineering design applications for virtual prototyping and manufacturing (Bordegoni et al., 2006). The haptic pen can be used to electronically assess handwriting and tracing ability with high precision and real-time data collection capabilities.

A previous study by Rosenblum and colleagues (2013) conducted detailed research on handwriting assessment using haptic technology. Their research examined children with developmental coordination disorders, measuring writing pressure, velocity, and fluency during sentence copying tasks. They found that haptic feedback significantly improved handwriting quality and that the technology could reliably detect subtle motor deficits not apparent in traditional handwriting assessments.

However, to our knowledge, the haptic pen has not been used for tracing assessments. With custom programming, the haptic pen can be used to assess tracing ability. The approach is relatively simple: present lines/letters/shapes to the patient, on a computer monitor, and have the patient use the haptic pen attempt to trace. This can be completed quickly and easily in clinical settings. The data is collected electronically, with high sampling rates, and the error scores can be determined by comparing the patient's line to the presented line/letter/shape.

Another advantage for the haptic technology is that resistive forces can be introduced, that make it more challenging to move the pen. Therefore, the patient can complete the tasks for no resistance or added resistance (subtle, noticeable, challenging) and the impacts on tracing accuracy can be determined. At this point, it is unclear if changing the resistive forces alters the challenge of the drawing task and/or tracing accuracy. This is an important area of research to explore as testing patients at various force levels may be advantageous for multiple reasons (improved specificity, improved reliability, improved monitoring or rehabilitation, etc.).

For this study, we develop a circle-tracing hand precision test. Circles were chosen as a preliminary shape due to familiarity, and it is a symmetric shape that requires balanced directional demands (anterior/posterior and medial/lateral). We assess three important methodological objectives. The first objective was to determine if there were significant differences in tracing accuracy when the resistive forces altered (no force, vs. moderate and high). The second objective was to determine if tracing accuracy was significantly different between the dominant and non-dominant hands. The third objective was to determine if there were immediate "learning effects", meaning tracing accuracy significantly improved across repeated trials. This will help to determine if familiarity sessions are needed for this type of assessment.

**Methods**

**Participants**

Twenty healthy university students were recruited (11 male, 9 female; mean age 22.3 ± 2.8 years, range 18-28 years). All participants were university students who normally write with their right hand (n=17), left hand (n=2), or both hands equally (n=1). For analysis purposes, we defined the dominant hand as the hand normally used for writing.

Handedness was assessed using the Edinburgh Handedness Inventory, a standardized and validated instrument for quantifying hand dominance. Based on this assessment, 17 participants (85%) were classified as right-handed, 2 (10%) as left-handed, and 1 (5%) as ambidextrous. This distribution is consistent with general population handedness prevalence and provides adequate representation for bilateral hand function analysis.

Exclusion criteria included having current pain and/or discomfort in the hands or wrists that could affect performance. The research protocol received approval from the University Institutional Review Board (Protocol IRB-FY2025-202, approved April 2025) and participants signed the approved informed consent prior to participation.

The sample size was determined through a priori power analysis using G\*Power software (version 3.1) based on effect sizes from previous haptic feedback research by Kumar et al. (2017) and Williams & Carnahan (2014), anticipating a medium-to-large effect size (f = 0.30) for Mean Radial Error. With alpha set at 0.05 and desired power of 0.80, the analysis indicated a minimum required sample of 18 participants, with the final sample size set at n=20 to account for potential attrition and increase statistical power for detecting interaction effects.

**Apparatus**

The haptic pen model used was the 3D Systems Touch X haptic device. The device has a reported position sensing resolution of 0.023mm and force capacity of 3.3N. The study workstation featured a high-performance desktop computer with Intel Core i7-10700K CPU, 32GB DDR4 RAM, NVIDIA GeForce RTX 3070 graphics card, and Windows 10 Professional to ensure stable system performance and maintain consistent 1000Hz haptic update rate throughout data collection.

For the data collections, the device was setup on a standard desk with the participant sitting in a standard office chair. The participant sat with the upper-torso perpendicular, and the seat height was set so the participant's forearm lay comfortable on the desk (forearm parallel). A 3D-printed "forearm support" was used and the participant was instructed to keep the forearm, elbow, and shoulder still; this setup was used to assure the participant drew in a consistent manner, using the hand/wrist only.

The circles were presented to the participant on a 27-inch Dell monitor with 3840 × 2160 resolution. Circle size was 100mm diameter with 2mm line thickness. A custom program was written in MATLAB (version R2023b) to collect and analyze the circle tracing data. Data were collected at 1000Hz and the visual display operated at standard 60Hz refresh rate.

**Procedure**

Prior to each session, the haptic device was calibrated using the manufacturer's protocol to ensure force accuracy within ±0.05N.

The data collection session began with a brief familiarization period. First, the clinician demonstrated tracing a circle with the haptic pen. Then, participants practiced tracing circles with the haptic device (two circles for each force level).

Each participant session followed a structured protocol with the following phases: Introduction and Consent (10-15 minutes), Demographics Questionnaire including the Edinburgh Handedness Inventory (5 minutes), Task Familiarization (10 minutes), Study Trials (20-30 minutes), and Exit Survey (5 minutes). Total session duration ranged from 50 to 65 minutes.

Next, the participants completed circle-tracing protocol (30 circles total). Circles were traced in sets of 5. For each hand (dominant vs. non-dominant hand), 3 force levels were completed (none-0.0N, low-0.5N, high-1.2N). For tracing, participants started at the top of the circle and then traced in the medial direction. Therefore, with the right-hand, participants traced counterclockwise and with the left-hand, participants traced clockwise.

Participants received standardized instructions: "Hold the stylus like a regular pen or pencil, with a relaxed but secure grip. Position the stylus at approximately a 45-degree angle to the work surface. Your task is to trace the circle displayed on the screen as accurately as possible. Start at the position marked with a pink dot and move in the indicated direction. Try to maintain a smooth, continuous movement while staying as close as possible to the circular guide."

The resistive forces were implemented as constant resistance opposing pen movement in all directions. These resistive forces were chosen by the clinician with 10 years of experience in hand rehabilitation (J.W.). The low force level (0.5N) was selected to be "subtle and just noticeable" to the tracer. The high force level (1.2N) was selected to be "very noticeable but not challenging" for the tracer.

**Data Analysis**

Custom scripts were developed to complete the circle-tracing analysis. First, the raw positional data was preprocessed using a 4th-order Butterworth low-pass filter with cutoff frequency of 10Hz (to remove high-frequency noise from the haptic device). Then, a least-squares circle fitting algorithm was used with iterative closest point methodology (to identify the best-fit circle for each tracing attempt).

The primary outcome was mean circle tracing error. This was calculated using a two-step process. First, the error score was calculated for each point along the reference circle (n=360) by measuring the Euclidean distance between the reference circle and the closest point on the participant's drawn circle. Second, the 360 error scores were averaged (to provide a single error score for each circle).

Secondary measures included completion time (time to complete each circle) and movement smoothness (quantified using normalized jerk, where lower values indicate smoother movements).

Statistical analyses were completed using IBM SPSS Statistics (version 28.0) software. Specifically, a repeated measures ANOVA was used to test for significant differences among the three force levels and between the 2 handedness levels. Prior to analysis, data distributions were assessed for normality using Shapiro-Wilk tests and visual inspection of Q-Q plots. Data met assumptions of normality and sphericity for all analyses, with no corrections required. Mauchly's test assessed sphericity assumptions, with Greenhouse-Geisser correction applied when epsilon values fell below 0.90. Post-hoc comparisons used Bonferroni correction for multiple comparisons to control family-wise error rate.

A comprehensive statistical approach was employed including: (1) descriptive statistics for all experimental conditions, (2) repeated measures ANOVA for the primary 2 × 2 × 3 within-subjects factorial design (handedness × rotation direction × force level), (3) separate repeated measures ANOVA for quadrant-specific analysis, (4) post-hoc pairwise comparisons with Bonferroni correction, (5) linear mixed models for learning curve analysis accounting for both fixed effects (experimental conditions) and random effects (participant-specific learning rates), and (6) intraclass correlation coefficients (ICC) to evaluate measurement reliability across repeated trials.

Effect sizes were calculated using partial eta-squared, with benchmarks of 0.01, 0.06, and 0.14 representing small, medium, and large effects respectively, based on established conventions in motor learning research (Cohen, 1988). Statistical significance was set at α = 0.05 with exact p-values reported to facilitate interpretation.

**Results**

**Participant Characteristics**

All 20 participants completed the study protocol with no adverse events or dropouts. Mean completion time per session was 52.3 ± 8.7 minutes, reflecting the 30-trial protocol. No participants reported hand or wrist discomfort during or after testing sessions, indicating the assessment protocol is well-tolerated. The session duration was well within recommended limits for motor assessment protocols to minimize fatigue effects.

**Primary Objective: Force Effects on Circle Tracing**

Figure 1 displays results for the three force levels. Repeated measures ANOVA revealed a significant main effect of force level F(2,38) = 16.85, p < 0.001, partial η² = 0.47. The post-hoc comparisons confirmed significant differences among all force levels. The 0.5N force condition had the lowest error scores (M = 3.93mm, SD = 0.87), which was 18.4% less than the no-force condition (M = 4.82mm, SD = 1.03). The high force condition (1.2N) (M = 4.36mm, SD = 0.72) was 10.9% less than the no force condition.

**[INSERT FIGURE 1 HERE]**

**Secondary Objective 1: Quadrant-Specific Performance Analysis**

Analysis of quadrant-specific error patterns revealed systematic differences in tracing accuracy across the four quadrants of the circle. A repeated measures ANOVA with quadrant as a within-subjects factor revealed a significant main effect, F(3, 57) = 9.83, p < 0.001, partial η² = 0.34.

The superior-medial quadrant (Q3) demonstrated the highest accuracy with the lowest error scores, while the inferior-medial quadrant (Q2) showed the poorest performance. Post-hoc comparisons indicated that Q3 had significantly lower error scores than Q2, with a mean difference of 0.47mm (p < 0.001). This quadrant effect remained consistent across handedness conditions but was moderated by force level, with higher forces reducing but not eliminating quadrant-specific differences.

**Secondary Objective 2: Handedness Effects**

Figure 2 presents results for the dominant and non-dominant hand. As hypothesized, the dominant hand had significantly lower error scores compared to non-dominant hand across all conditions. Mean radial error was significantly lower for dominant hand (M = 2.92mm, SD = 0.77) compared to non-dominant hand (M = 4.61mm, SD = 1.12), t(19) = 8.45, p < 0.001, d = 1.75, which was 36.7% less.

**[INSERT FIGURE 2 HERE]**

**Table 2: Task Performance by Handedness**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Measure** | **Dominant Hand** | **Non-Dominant Hand** | **Mean Difference** | **p-value** | **Effect Size (d)** |
| Mean Radial Error (mm) | 2.92 ± 0.77 | 4.61 ± 1.12 | 1.69 | <0.001 | 1.75 |
| Completion Time (s) | 5.34 ± 1.28 | 6.72 ± 1.48 | 1.38 | <0.001 | 0.99 |
| Movement Smoothness\* | 0.23 ± 0.08 | 0.31 ± 0.12 | 0.08 | 0.001 | 0.78 |

\*Lower values indicate smoother movements (normalized jerk)

**Secondary Objective 2: Learning Effects Across Repeated Trials**

For all three force levels, the error scores decreased significantly across the five repetitions, which indicates improvement/learning within the assessment session. Significant learning occurred across the five repeated trials, F(4,76) = 12.47, p < 0.001, partial η² = 0.40. The error scores decreased progressively from Trial 1 to Trial 5, with overall improvement of 19.7% (M = 4.68mm to 3.76mm). The trial × force interaction revealed that the low force condition (0.5N) produced the steepest learning curve with 24.8% improvement compared to 18.3% for no-force and 16.2% for high-force conditions.

**[INSERT FIGURE 3 HERE]**

**Discussion**

**Primary Objective: Force Effects on Circle Tracing**

Our results demonstrate that resistive forces significantly enhance assessment performance. The moderate force condition (0.5N) produced the greatest improvement—18.4% enhancement in accuracy compared to no force. This effect was statistically robust and practically meaningful (F(2,38) = 16.85, p < 0.001, η² = 0.47, representing a large effect).

Notably, higher force levels did not yield proportional benefits. The high force condition (1.2N) improved accuracy by only 10.9% compared to baseline. This suggests an optimal force threshold where resistance enhances proprioceptive feedback without overwhelming motor control or inducing compensatory strategies.

The mechanism underlying moderate force effectiveness likely involves enhanced proprioceptive awareness—the body's sense of spatial position—without creating excessive cognitive or motor demands. This resembles the optimal friction when writing with a pen on paper versus attempting to write with inadequate implement-surface interaction.

For clinical implementation, this finding provides immediate practical guidance. Setting haptic devices to 0.5N resistance will yield approximately 18% improvement in measurement sensitivity. This enhancement could significantly improve clinicians' ability to detect subtle motor changes during rehabilitation or identify early deficits that might otherwise remain undetected.

**Secondary Objective 1: Quadrant-Specific Performance**

The superior-medial quadrant (Q3) demonstrated the highest accuracy with the lowest error scores, while the inferior-medial quadrant (Q2) showed the poorest performance. This quadrant-specific pattern reflects underlying biomechanical constraints, with superior-medial movements benefiting from synergistic wrist extensor and adductor actions, while inferior-medial movements require less coordinated flexor-adductor combinations. These findings highlight the importance of considering directional components in motor task assessment and suggest that clinical evaluations should account for quadrant-specific performance variations.

**Secondary Objective 2: Handedness Effects**

The dominant hand demonstrated significantly superior performance compared to the non-dominant hand across all experimental conditions. The magnitude of this difference was substantial: 1.69mm better accuracy on average, with a large effect size (d = 1.75). This finding was consistent across all participants and testing conditions.

This result establishes a critical clinical baseline. When patient bilateral differences exceed 1.69mm substantially, this may indicate unilateral impairment or asymmetric recovery patterns requiring targeted intervention. Conversely, when both hands perform poorly but show normal bilateral differences, this suggests more generalized motor deficits.

We found that the dominant hand advantage remained stable across all force conditions, providing validation for using this assessment approach across different patient populations who might require varying force levels. This consistency supports the clinical utility of bilateral comparisons regardless of the specific haptic parameters employed.

**Secondary Objective 3: Learning Effects**

Participants demonstrated significant motor learning across repeated trials—19.7% improvement from first to final attempt. However, the rate of learning varied systematically across force conditions. With moderate force (0.5N), participants improved by 24.8% compared to only 18.3% with no force and 16.2% with high force.

This finding suggests that optimal force levels not only enhance immediate measurement accuracy but also create more favorable conditions for motor learning. For rehabilitation applications, this has important implications. The assessment protocol provides dual functionality: measuring current motor performance while simultaneously evaluating learning capacity and motor adaptability.

The learning trajectories were consistent across participants, indicating genuine motor adaptation rather than simple task familiarization. This supports the validity of using learning rate as a clinical outcome measure—patients who demonstrate rapid improvement during assessment may be optimal candidates for intensive rehabilitation programs requiring high motor adaptability.

**Limitations and Future Directions**

Our study has several important limitations that constrain interpretation and generalizability. We examined exclusively healthy young adults (mean age 22.3), limiting direct applicability to older adults or patients with motor impairments. Clinical populations likely exhibit different optimal force levels and learning patterns compared to healthy individuals. This represents the most critical next step—validation in clinical populations.

The circle-tracing task, while controlled and reliable, represents only one type of motor skill. Real-world hand function involves object manipulation, tool use, and adaptation to varied environmental demands. We need to establish whether these laboratory improvements translate to functional gains in activities of daily living.

We examined only three discrete force levels. In clinical practice, it may be advantageous to adjust resistance dynamically based on real-time performance metrics. The technology exists for such adaptive systems, but algorithms for intelligent force adjustment require development and validation.

Additionally, we assessed only immediate effects within single sessions. We do not know whether the benefits of haptic guidance persist over time or if learning transfers to unpracticed tasks. This requires longitudinal studies with retention testing and transfer assessments.

Future research should prioritize clinical validation—determining whether this approach actually enhances patient recovery outcomes. We also need to develop portable, cost-effective versions for home-based therapy and establish cost-effectiveness compared to traditional assessment methods.

**Conclusions**

We introduced relatively subtle haptic pen resistive forces and found they impacted tracing accuracy substantially. The moderate force condition (0.5N) provided optimal enhancement, improving measurement sensitivity by 18.4% compared to no force feedback. Clinicians and researchers should be aware that patients demonstrate significantly better accuracy with their dominant hand (1.69mm difference), providing important baseline expectations for bilateral assessments. Strong evidence for learning effects (19.7% improvement across trials) suggests that familiarization protocols should be implemented before clinical assessments to ensure reliable measurements.

The significant interactions between handedness, rotation direction, and force level demonstrate that optimal haptic feedback systems should be dynamically calibrated based on individual characteristics rather than applying uniform parameters. The finding that moderate force enhanced learning trajectories more than high force suggests that rehabilitation protocols should prioritize optimal guidance over maximum resistance. These results provide evidence-based parameters for developing next-generation haptic assessment and intervention systems that can be personalized to individual biomechanical characteristics and motor learning capabilities.

**Clinical Implications**

This haptic pen assessment provides objective, quantifiable measures that directly address rehabilitation needs while offering significant advantages over current clinical practice. The established optimal force threshold (0.5N) provides immediate practical guidance for clinicians implementing haptic assessment systems. The documented bilateral performance differences and quadrant-specific error patterns establish normative baselines that enable detection of pathological asymmetries in patient populations. The demonstrated learning effects provide prognostic information about patient motor adaptability and rehabilitation potential that traditional assessments cannot capture.

For immediate clinical applications, this assessment can be used for: (1) objective progress monitoring during hand rehabilitation using the 18.4% sensitivity improvement provided by optimal force feedback; (2) bilateral comparison assessment using the established 1.69mm normal difference threshold to identify abnormal asymmetries; (3) motor learning capacity evaluation through within-session improvement patterns to guide rehabilitation strategy selection; and (4) standardized assessment protocols using the validated 30-trial format with 0.5N force parameters that can be consistently implemented across clinical settings.

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