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A Pilot Study of the Effects of Pulley Location and Design Parameters on Hand Movements during Pulley Threading Operations

Justin M. Haney[1], **Mary Owczarczak**[1], **Clive D'Souza**[1], **Monica L. H. Jones**[2], and **Matthew P. Reed**[1,2]

[1]Department of Industrial and Operations Engineering, University of Michigan, Ann Arbor, MI, USA

[2]University of Michigan Transportation Research Institute, Ann Arbor, MI, USA

Abstract

Three healthy individuals participated in a laboratory experiment that required routing a thin continuous thread through a series of pulleys mounted on a vertical work surface. Task precision demand was manipulated by altering pulley outer diameter (38 mm, 76 mm, and 152 mm) and groove width (3 mm, 6 mm, and 9 mm). The target location of each destination pulley relative to the origin at the mid-sagittal plane was also manipulated. These factors were hypothesized to influence hand motion trajectories, peak speed, and task completion time. Smaller pulley diameters and larger groove widths, representing lower precision demands, were associated with smoother trajectories and a faster task completion time. These preliminary findings suggest a systematic influence of task precision demands on movement kinematics and task performance.

INTRODUCTION

Low force, high precision work is a staple of many manual material handling jobs in industry. A specific category of jobs involves handling and manipulating long, continuous and potentially fragile material such as thread and wire. Examples include textile manufacturing, electrical wiring, and automobile wire harness assembly. Constraints in the work environment such as occluded line of sight, hard to reach target locations, and small clearance spaces place additional demands on human performance and safety. Improving the design of the workstation for high-precision handling of continuous material requires a systematic investigation of the impact of task demands on movements, hand and body posture adaptions, and task performance.

Hand postures and motions in tasks that involve grasping and manipulating a discrete work object have been extensively investigated (Bootsma & van Wieringen, 1992; Marteniuk et al., 1990; Zaal & Bootsma, 1993). These prehension tasks are composed of a grasp or manipulation component and a transport or reach component. These components have been shown to be directed by visual information about the target object's size, shape, location, and orientation relative to the operator. Object location has been found to impact hand acceleration, peak velocity, and movement time during the reaching phase of a prehension task (Marteniuk et al., 1987) while object shape and size have been shown to affect hand kinematics during the deceleration stage of the reaching phase (Marteniuk et al., 1990).

Additionally, researchers have investigated the impact of object size and target precision on movement time during object positioning tasks under both one-handed (Srinivasan & Martin, 2008; Srinivasan et al., 2013) and two-handed (Srinivasan et al., 2013) task conditions. In these tasks, an initial open loop movement phase is followed by a closed loop phase with feedback, with the transition timing affected by the object characteristics and target precision requirements. However, these studies have focused on discrete reaching movements and do not describe operator performance during sequential tasks that involve targets with a range of characteristics (e.g., precision) and location.

In this pilot study, hand motion trajectories were measured as participants routed a continuous thread through a set of pulleys. The objective was to determine the effects of pulley design parameters and pulley location on hand motion trajectories, peak speed, and task completion times.

METHODS

Participants

Sample results from three healthy young adults, one man (20 years old) and two women (20 and 21 years old), that participated in the experiment are presented in this paper. All participants were right-handed, free of any musculoskeletal disorders, and had normal or corrected vision. Additionally, they had no prior experience performing the type of activity conducted in the experiment. This experiment was approved by an Institutional Review Board at the University of Michigan.

Experiment Setup

The experiment apparatus consisted of a height- adjustable acrylic work surface (1.49 m x 1.49 m) oriented vertically so that the pulley axes were all horizontal and parallel (Figure 1). Targets for the threading task consisted of custom-designed nylon pulleys that were mounted on the work surface in a desired configuration (sequence). Task precision demand was altered by varying the pulley design parameters, namely, outer diameter (OD) and groove width (GW). Nine pulley designs derived from a combination of three ODs (38 mm, 76 mm, and 152 mm) and three GWs (3 mm, 6 mm, and 9 mm) were tested in the experiment.

Five possible target locations were investigated in this experiment (Figure 2). Pulleys were mounted on the perimeter of a semicircle with a radius of 46 cm at angles of 0° (3 o’clock position), 45°, 90°, 135°, and 180° (9 o’clock position) relative to a constant origin pulley located at the center (Figure 2).

The work surface height was adjusted to align the origin pulley with each participant’s standing elbow height. Participants stood at a comfortable distance away from the work surface and could self-select body postures and movements (e.g., side step or lean closer) during the trials to complete the threading tasks. The 100% polyester thread (Coats & Clark, Dual Duty XP Heavy Thread) was pulled from a spool located on the right edge of the work surface. The apparatus was designed so that the thread tension remained at a low level throughout the operation.

Experiment Procedure

Each trial began with the participant grasping the end of the polyester thread from the spool with their right hand using a thumb-forefinger pinch grip. After grasping the thread, the participant moved their hand end effector over to a known marker located on the spool for a static 3-second calibration pose (Figure 3) after which the threading task could commence.

The participant threaded a sequence of five consecutive origin-destination pairs of pulleys in the direction depicted in Figure 2. The origin location was constant throughout each trial. The destination pulleys were all threaded in a clockwise direction and constant order, i.e., starting with $\theta_1 = 180°$ and moving in a clockwise direction between origin-destination pairs until θ_5 (= 0°) and returning back at the origin.

Presentation of destination pulleys was counterbalanced to include every combination of OD x GW x Target Location. Participants performed three repetitions for each task condition. Participants were instructed to complete the task as quickly as possible while threading all pulleys successfully. Three practice trials prior to data collection were provided to familiarize participants with the task.

Instrumentation

An optical motion capture system (Optotrack Certus, Northern Digital Inc.) was used to measure hand movements at 100 Hz. An active-marker triad located on the back of the participants' right hand was used to estimate the position of the thumb-forefinger pinch grip based on the pretest calibration measurement (Figure 3). Three-dimensional coordinate data from the motion capture system was filtered using a 2^{nd}-order low-pass Butterworth filter with a 6-Hz cut-off frequency. Two-dimensional end effector position data in frontal plane (i.e., parallel to work surface) was computed and used in a qualitative and quantitative analysis of hand motion trajectory and task performance.

Data Analysis

End effector trajectories were plotted for each task condition to visually examine for influence of OD, GW, and target location on end effector trajectory shape. Each motion trial was segmented into five origin-destination threading tasks based on the five target locations. The start time for each threading task was determined by the time point at which the end effector first crossed the centerline between an origin-destination pulley pair at the origin, and the end time was determined by the time point at which the trajectory first crossed the centerline on the return to the origin.

Each threading task was divided into three phases based on speed of the end effector: (1) Reach: reaching toward the destination pulley, (2) Dwell: threading of the destination pulley, and (3) Return: returning to the origin. The dwell phase was identified as the instant at which the resultant end effector speed was less than 25% of the peak speed during the reach phase to the instant it exceeded 25% of the peak speed during the return phase.

Summary statistics for the peak speed during the reach phase, task completion times, and percent time spent in the dwell phase were computed for each task trial, averaged over three repetitions and compared across OD, GW, and Target Location.

RESULTS

A visual comparison of end effector trajectories revealed similar shape patterns across the sample of study participants. End effector trajectories for a sample participant data are shown in Figure 4 for each pulley design parameter combination (OD x GW) when the destination pulley was located at the 0° target location.

In general, GW and target location appeared to have the biggest influence on shape of the trajectory. Smaller pulley diameter and larger groove width resulted in a more rounded (smooth) dwell phase. Conversely, a jagged trajectory was observed with decreasing GW size (GW = 3 mm) and target locations of 135° and 180°.

Tables 1, 2 and 3 list the pooled mean and standard deviations for peak speed during the reach phase, task completion time, and percent time spent in the dwell phase, respectively. For a constant OD, a consistent trend of lower (faster) task completion times with increased GW was observed. The trend across OD for a given GW was less consistent, though a noticeable increase in completion time at OD = 152 mm was noted, possibly due to the greater groove length engaged by the thread. On average, increases in GW corresponded with decreases in total task time and percent time spent in the dwell phase. Peak speed during the reach phase, total task time, and the percent time spent in the dwell phase all appeared to be impacted by OD and GW, irrespective of target location. Higher peak hand speeds were found with decreasing OD, while the effect of GW varied across OD.

Table 4 provides a summary for peak speed during the reach phase, total task time, and percent time spent in the dwell phase stratified by Target Location (Table 4). In general, the effect of target location on task performance was similar across the sample of study participants. Target locations to the right of the participants (angles of 0° and 45°) tended to produce the lowest peak speeds. Similarly, destination pulleys located to the right of the participants (angles of 0° and 45°) and directly in front (angle of 90°) resulted in a decrease in total task time and percent time spent in dwell phase when compared to the left side (angles of 135° and 180°).

DISCUSSION

In this pilot study of pulley threading, target location and pulley design parameters affected hand motion trajectories shape, hand speed, task completion time, and the fraction of the total motion time in the dwell phase. Increases in GW size and target locations to the right of the participants corresponded with smoother end effector trajectories and faster task completion times while the impact of OD size varied across participants. Additionally, the impact of pulley design parameters tended to be independent of target location.

These trends are consistent with the expected effects of increased precision demand and line of sight constraints with the target groove. The precision demand was determined by the size of the GW. The larger GWs, indicating lower levels of precision, provided a larger target for the participants which made the threading tasks inherently simpler. Additionally, line of sight with the target groove varied across the target locations due to the requirement to thread the destination pulleys in a clockwise direction around the pulley axis. The line of sight for pulleys located on the contralateral side of the work surface was obstructed by the face of the pulley in a neutral standing posture. Increases in the difficulty of the threading task reduced trajectory smoothness and increased in task time as multiple attempts were required to thread the pulley. Compensatory strategies to improve visual and manual access, such as reaches, side stepping, and lateral torso bending were sometimes observed.

In the Fitts' law model of control of human movement (Fitts, 1954), the index of difficulty, a function of distance between targets and target width, is suggested as an indicator of movement time between targets in a reciprocal tapping task. However, in this study the target of the precision reach task consists of multiple characteristics including the pulley design parameters and the target location relative to the origin. The current task variables OD, GW and Target Location present a modified index of difficulty specific to this task, though the precise relationship between these characteristics and their impact on movement time requires further investigation.

This pilot study is limited by the small number of participants. Due to the sequential properties of the task, individual origin-destination task trials needed to be extracted from the entire sequence. The start and end times for each trial were determined by the position of the end effector trajectory and did not account for the initial hand speed, which varied somewhat with target location. The participants did not have previous experience with this task and hence their performance is likely to be poorer than experienced operators. However, the findings were similar across the three participants. Further investigation is needed to develop a model of human performance in pulley threading tasks that is sufficiently general and robust for use in ergonomic analysis.

Acknowledgments

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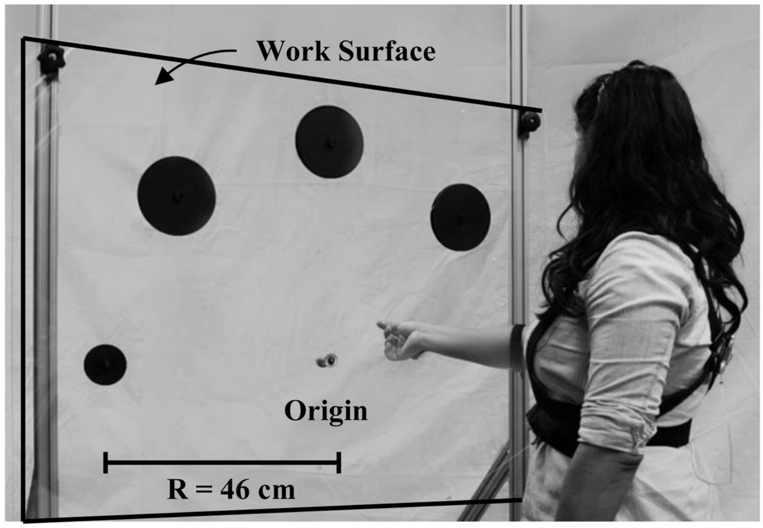

Figure 1.
Experiment apparatus and setup

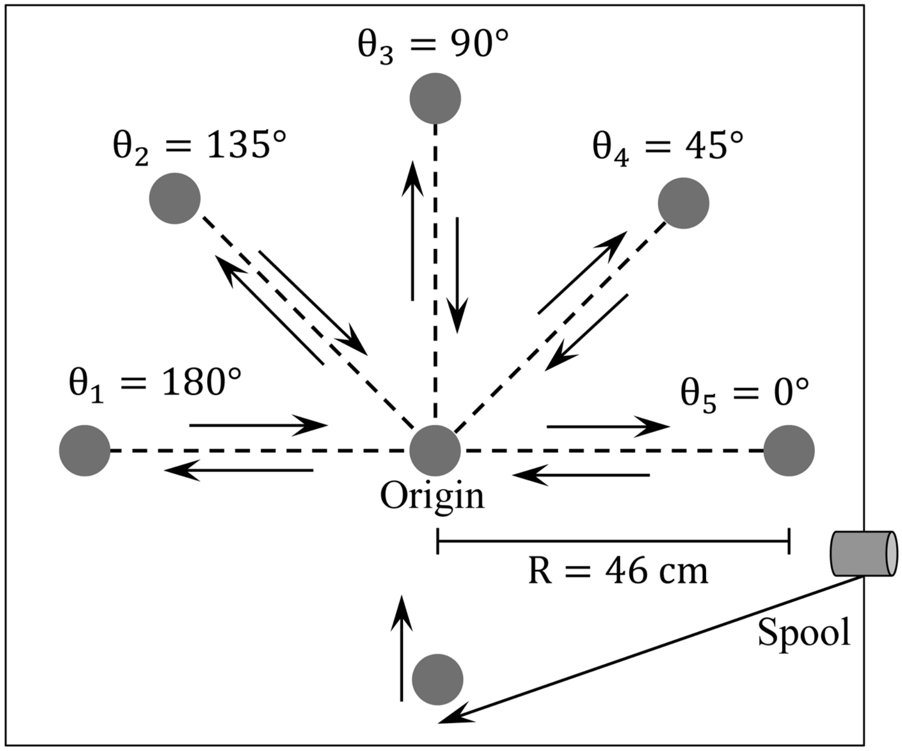

Figure 2.
Schematic depicting the location of origin and destination pulleys on the work surface. Arrows depict the direction of threading during the experiment trials.

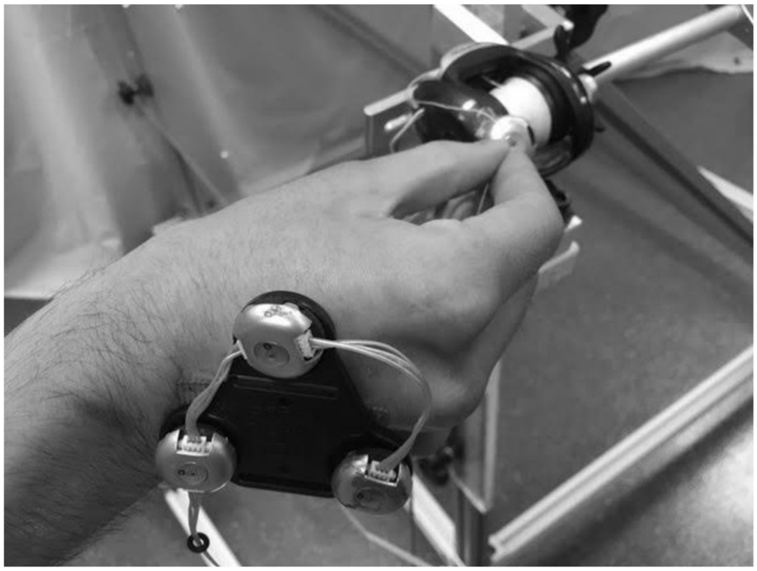

Figure 3.
Pretest calibration to predict end effector position using the hand marker triad.

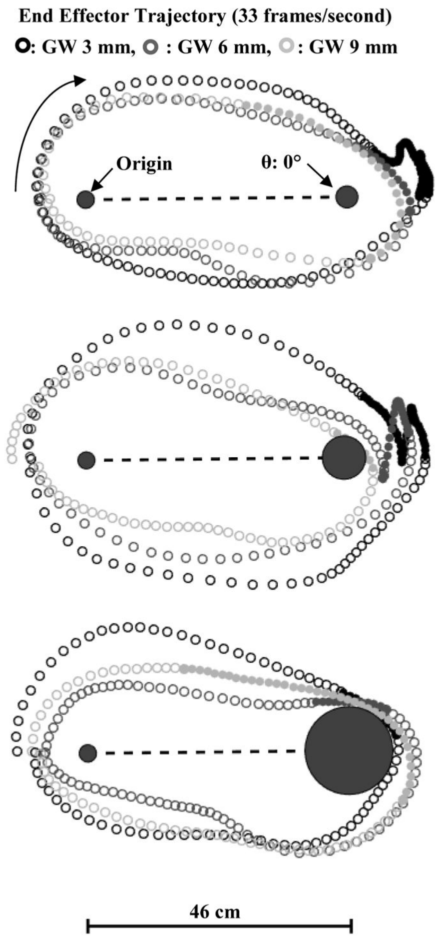

Figure 4.

Sample participant data showing the end effector trajectory when threading a target pulley located at 0° (i.e., moving to a 3 o'clock position and back). Panels (from top to bottom) depict increase in pulley outer diameter (OD). Within each panel, data trajectories depict the influence of changing groove width (GW). The dwell phase for each trajectory is indicated by filled in circles.

Table 1

Mean ± SD values for peak speed (mm/s) for the end effector during the reach phase stratified by pulley outer diameter (OD) and groove width (GW).

	OD: 38 mm	**OD: 76 mm**	**OD: 152 mm**
GW: 3 mm	993 ± 173	1044 ± 57	918 ± 49
GW: 6 mm	1025 ± 159	999 ± 96	914 ± 133
GW: 9 mm	1063 ± 118	934 ± 91	953 ± 175

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Table 2

Mean ± SD values for task completion time (s) stratified by pulley outer diameter (OD) and groove width (GW).

	OD: 38 mm	**OD: 76 mm**	**OD: 152 mm**
GW: 3 mm	3.29 ± 0.56	3.21 ± 0.59	3.84 ± 0.69
GW: 6 mm	2.83 ± 0.42	2.81 ± 0.49	3.32 ± 0.43
GW: 9 mm	2.47 ± 0.41	2.72 ± 0.45	3.27 ± 0.33

Table 3

Mean ± SD values for percent time spent in dwell phase (%) stratified by pulley outer diameter (OD) and groove width (GW).

	OD: 38 mm	**OD: 76 mm**	**OD: 152 mm**
GW: 3 mm	29.9 ± 6.3	34.9 ± 7.7	31.6 ± 8.2
GW: 6 mm	29.0 ± 10.7	25.6 ± 4.1	25.0 ± 7.6
GW: 9 mm	26.1 ± 1.5	21.2 ± 4.8	26.4 ± 5.0

Table 4

Effect of target location on peak speed, total task time, and percent time spent in dwell phase.

Target Location	Peak Speed (mm/s)	Task Completion Time (s)	% Time in Dwell Phase
0°	851 ± 103.9	3.19 ± 0.52	22.7 ± 6.4
45°	958 ± 109.5	2.75 ± 0.51	22.8 ± 4.0
90°	1072 ± 80.2	2.75 ± 0.41	27.0 ± 3.5
135°	1040 ± 90.2	3.42 ± 0.52	34.6 ± 6.3
180°	992 ± 97.8	3.32 ± 0.61	31.5 ± 5.8