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# Spatial and Temporal Patterns in Sequential Precision Reach Movements

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## Introduction

Sequential reach tasks are a common component of manual assembly jobs. These tasks typically involve manipulating a work object or material and reaching to successive target locations with different precision requirements. Ergonomics research on the control of hand movements has largely focused on tasks requiring discrete reaches (e.g., Bootsma & Van Wieringen, 1992; Hoff & Arbib, 1993; Jeannerod, 1984; Marteniuk et al., 1990).

The objective of this paper was to investigate spatial and temporal effects of pulley design parameters (outer diameter and groove width) on the trajectory of the threading hand in sequential reaches with different precision requirements. Additionally, we propose a scheme to segment hand trajectories into control phases based on the fingertip trajectory speed profile. Segmenting sequential reach tasks into discrete movements between two consecutive target locations will be useful towards developing models of sequential reaching movements and performance for ergonomic analysis.

## Methods

Twelve right-handed adults, ages 20–26 years, participated in a laboratory experiment that required threading polyester string through a system of pulleys mounted on an acrylic work surface. Interchangeable pulleys were arranged on the perimeter of a semicircle with a radius of 46 cm at azimuths of 0°, 45°, 90°, 135°, and 180° relative to a constant origin pulley located at the center. The height of the pulleys above the floor was adjusted to place the center pulley at the participant's standing elbow height. The thread was pulled from a spool located below the center pulley. The task involved threading the pulleys in the following sequence: origin-180°-origin-135°-origin-90°-origin-45°-origin-0°-origin. We conducted a full-factorial experiment with three pulley outer diameters (OD: 38-mm, 76-mm, and 152-mm), three groove widths (GW: 3-mm, 6-mm, and 9-mm), five pulley locations (0°, 45°, 90°, 135°, and 180°), and two threading directions (clockwise and counterclockwise), with 3 repetitions per condition. Participants were instructed to complete the task as quickly as possible while also ensuring each pulley was threaded successfully.

A motion capture marker triad on the hand dorsum tracked hand motions during the task. Hand trajectories were analyzed separately for each of the 5 origin-destination pulley location pairs. Speed profiles were analyzed to identify transition points between the transport phase, where the hand is reaching from the origin to the destination location, and the pulley interaction phase, where the hand is engaged in threading the destination pulley. The start and end points of the pulley interaction phase correspond to the first and last local speed minima that occur below a threshold set at 100-mm/s above the minimum speed when the trajectory is within the region of the destination pulley. The angle ($\alpha$) and radius ($R$) of the hand position, relative to the destination pulley center, were estimated at the start ($t_1$) and end ($t_2$) points of the pulley interaction phase. Repeated measures ANOVA was used to test the effects of OD, GW, pulley location, and threading direction on the time spent in the pulley interaction phase ($T_{PI} = t_2 - t_1$), $R_1$, $R_2$, $\alpha_1$, $\alpha_2$, and the difference between $\alpha_1$ and $\alpha_2$ ($\alpha_{PI} = \alpha_2 - \alpha_1$).

## Results

### Temporal parameters

Pulley OD ($p < 0.001$), GW ($p < 0.001$), location ($p = 0.002$), and the threading direction x pulley location interaction ($p < 0.001$) had a significant effect on $T_{PI}$. Larger GW corresponded to less $T_{PI}$ (GW: Mean±SE, 3-mm: 772±34 ms, 6-mm: 473±23 ms, 9-mm: 351±18 ms). Pulley OD of 152-mm required significantly more $T_{PI}$ (713±35 ms) compared to the 38-mm (449±21 ms) and 76-mm (433±21 ms) OD. The CW threading direction required significantly less $T_{PI}$ for the 0°, 45° and, 90° pulley locations, while CCW threading direction took more $T_{PI}$ for the 135° and 180° pulley locations.

### Spatial Parameters

The effects of OD ($p < 0.001$) and pulley location ($p < 0.001$) were significant for $R_1$. Larger OD corresponded to increased $R_1$, i.e., 38-mm OD: 76±1-mm, 76-mm OD: 87±1-mm, and 152-mm OD: 119±1-mm. Additionally, $R_1$ increased significantly as the pulley location changed from 0°–180°. Similar trends were observed for $R_2$ across OD and pulley location. The main effects of OD ($p < 0.001$), pulley location ($p < 0.001$), and threading direction ($p < 0.001$) and the interaction between pulley location and threading direction ($p < 0.001$) were significant for $\alpha_1$. Larger OD corresponded to a greater $\alpha_1$ (38-mm OD: 24±1°, 76-mm OD: 34±1°, 152-mm OD: 53±1°). At the 180° pulley location, $\alpha_1$ was significantly greater for the CCW vs. CW threading direction. At the 0°, 45° and, 90° pulley locations, $\alpha_1$ was greater for the CW vs. CCW threading direction. Similar trends were observed for $\alpha_2$ across task parameters. The main effect of pulley OD on $\alpha_{PI}$ was significant ($p < 0.001$) with a larger $\alpha_{PI}$ for the 152-mm OD (22±1°) compared to the 38-mm OD (15±1°) and 76-mm OD (11±1°).

## Discussion

These results show that pulley design parameters in a sequential reach task systematically influence the spatial properties and transition timing of hand motion trajectories between phases. Narrower GW increased the precision requirement and corresponded to slower times. Participants took more time threading the larger OD. Shorter threading times occurred when participants had a direct line of sight with the pulley groove. Pulley OD influenced the radius of the hand position at the start and end of the pulley interaction phase, whereas pulley GW had no effect. The increase in $R_1$ and $R_2$ for pulleys located on the contralateral side compared to the lateral side was attributed to need for line of sight with the pulley groove since the hand obstructs the view of the pulley edge on the contralateral side.

## Conclusions

Analysis of sequential reaches needs to consider individual target locations and design parameters. Our findings also show the potential for modeling sequential reaches as a series of discrete reaches. A scheme to segment hand trajectories into control phases based on the fingertip trajectory speed profile was presented. Further investigation is necessary in sequential reach tasks with more realistic and complex work configurations observed in industrial settings.

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