Evaluating the Minimum Jerk Motion Model for Redirected Reach in Virtual Reality

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ABSTRACT
Reach redirection in virtual reality uses spatial distortion to augment interaction with passive props as well as active haptic devices. For such dynamic physical systems, motion modeling is needed to update the interface based on users' predicted targets & trajectories. However, it remains unclear how well standard predictive models hold under redirection. In this work we evaluate one such commonly used model, the Minimum-Jerk (MJ) model, during redirected reach at various lateral offsets up to 16cm. Results show that larger redirection significantly worsens MJ model fit, suggesting that models should be adjusted for reaches with considerable redirection. Predicted arrival times, based on fitting an MJ model on the first half of reach data, led to an average error of -0.29s for redirected reach, compared to -0.03s for normal reach.

Author Keywords
Haptics; Retargeting; Illusion; Perception; Virtual Reality.

CCS Concepts
•**Human-centered computing → Interaction techniques;** *Virtual reality; Empirical studies in HCI;*

INTRODUCTION
In recent years, researchers have explored Virtual Reality (VR) interaction techniques such as redirection [5] and retargeting [4], which warp the virtual space to guide the user's real hand to a different area in physical space. Such techniques leverage visual dominance, the tendency for vision to dominate sensory conflicts, to create a distorted mapping between the virtual and real worlds [16].

These perceptual illusions have been used to improve reach ergonomics [15], augment physical proxies [7, 19, 12, 11], and compensate for limitations of active haptic devices [2]. One such limitation is delay in response time. These delays are even more pronounced in encountered-type haptic devices, which must traverse the user's physical workspace to embody different virtual objects [17, 3, 18, 9]. To compensate for delays, researchers have used motion models to predict users' trajectories and adjust the haptic system preemptively [6].

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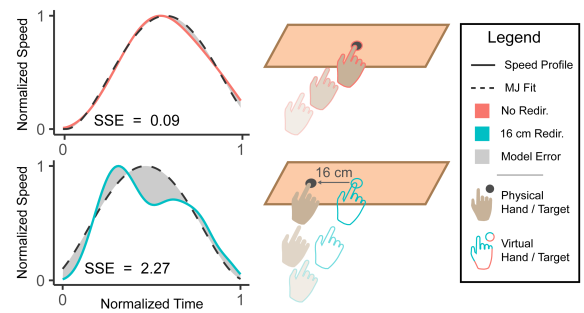

Figure 1. Representative hand velocity profiles during non-redirected reach (top) and 16 cm redirected reach (bottom). Dashed lines indicate MJ model fit and gray area indicates residual error. Redirected profiles tend to have elongated or humped tails, resulting in a worse fit.

We posit that both predictive motion models and redirection will be needed for immersive physical interactions in VR, particularly with dynamic haptic devices to compensate for delays, positional inaccuracies, and workspace limitations. The accuracy of such motion models, however, has not been evaluated during redirection.

This work takes a first step towards evaluating one such commonly used model, the Minimum-Jerk model (MJ), during redirected reach at various offsets up to 16cm (Figure 1). We hypothesize that the MJ model would fit worse for larger redirection above the noticeable threshold as users make more conscious, suboptimal movements to correct the offset.

THE MINIMUM-JERK MODEL
The Minimum-Jerk model (MJ) is a well-established model of multijoint arm movement, commonly used due to its simplicity and accuracy in replicating experimental data [10]. First proposed by Flash & Hogan [8], the MJ model suggests that humans minimize the derivative of their hand acceleration when executing reaching movements. For goal-directed reach, this results in a symmetric, bell-shaped hand speed profile described by a 4^{th} order polynomial, constrained to smoothly begin and end at 0 (Figure 1):

$$v(t) = A * (t - t_{start})^2 * (t - t_{end})^2 \quad (1)$$

Here $v(t)$ is hand speed, and A, t_{start}, and t_{end} are free parameters to be fit. These parameters model the peak velocity, start time, and stop time of the reach, respectively.

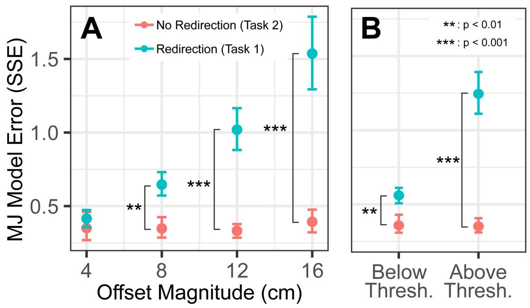

Figure 2. MJ model error by (A) offset and (B) grouped as below/above users' perceptual detection thresholds. Mean and 95% bootstrap confidence intervals shown.

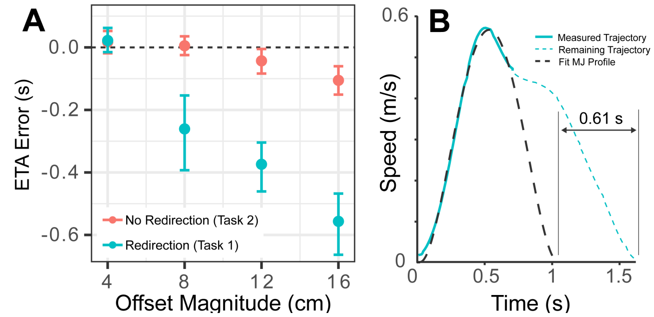

Figure 3. (A) Error in predicted ETA during redirected and non-redirected reach, computed using (B) an MJ model fit to 50% of sample trajectory (sample shown with 16cm redirection). Mean and 95% bootstrap confidence intervals shown.

STUDY DESIGN

To evaluate how well the MJ model describes redirected reach velocity profiles, we recruited 12 right-handed users (6F, 18-27) to participate in a two-task study. Users wore a VR headset and reflective finger markers tracked by an Optitrack system. In the virtual scene, users reached from a starting point to a 2cm circular target on a virtual table in front of them (15cm below, 40cm out). The virtual table was aligned with a physical table which provided passive feedback when the target was reached. Users first completed a redirection demonstration and a speed training session (desired reach time $\approx$ 1.5s).

Task 1 was an offset detection task. Following the method of constant stimuli, users experienced 5 levels of leftward redirection offsets (0, 4, 8, 12, 16cm measured laterally from a visual target aligned with their sagittal plane) 20 times each, randomized. After each reach, users indicated whether they detected the redirection and their confidence level (1-5). Only indications above a confidence level of 2 were counted as detection [1, 14]. The goal of this task was to record hand trajectories during redirected reaching at each level, and use users' indications to determine user-specific detection thresholds.

Task 2 was a simple target acquisition task where users reached to targets placed at the same physical locations (i.e., offset) described above, without redirection. This was done to compare normal and redirected reaches with the same start and endpoints. Task order was counterbalanced between participants.

EXPERIMENTAL RESULTS

Trials involving multiple reaches or missed targets were excluded. For each of the 1904 valid recorded reaches, we fit an MJ model to the normalized velocity profile and calculated the goodness-of-fit via sum of squared errors (SSE). From the offset detection task data, we then estimated the 50% detection threshold (DT) per subject (M: 9.5cm, SD: 1.4cm) and labelled each offset as above or below DT (see [1] for details on computing DT). For comparative analysis we define "offset" as leftward displacement of the physical target location from the subject's sagittal plane, independent of redirection.

A two-way repeated measures ANOVA revealed significant interaction between offset and redirection (i.e., task) on MJ SSE (F(1,1892) = 92.6, $p < 0.001$). For redirected reaches, offset had a significant effect (F(1,938) = 131.4, $p < 0.001$) increasing MJ SSE by about 0.09 $\pm$ 0.01 (SE) per cm. Intuitively, offset had no effect on non-redirected reaches (p = 0.48). The results of further post-hoc pairwise comparisons are shown in Figure 2A. These results show a clear deviation from the standard MJ model for reaches with considerable redirection. Figure 1 shows speed profiles from a single user representative of model deviations at the given SSE levels. We observe that larger redirection tends to elongate the profile's tail, at times creating a two-humped trajectory, likely caused by users' delayed corrective movements.

A second two-way repeated measures ANOVA revealed significant interaction between threshold and redirection on MJ-fit SSE (F(1,1889) = 65.8, $p < 0.001$). For redirected reaches, offsets above the detection threshold significantly increased MJ SSE (F(1,1895) = 141.9, $p < 0.001$) by 0.73 $\pm$ 0.06 (SE). Interestingly, redirection yielded larger MJ SSE for offsets both below subject-specific DTs (p = 0.005) and above ($p <$ 0.001) (Figure 2B). Prior work has shown that haptic feedback can reduce detection of visuo-proprioceptive illusion, inflating the DT [13]. It should be noted that MJ model errors may be insignificant below the DT found with no haptic feedback.

IMPLICATIONS & FUTURE WORK

One practical use of the MJ model is predicting users' Estimated Arrival Time (ETA) to a target by fitting a model to a portion of the observed speed profile [6]. The resulting fit parameter t_{end} in (1) provides an estimate for the reach end time. To contextualize the model deviations observed in terms of ETA, we fit an MJ model to the first 50% of each reach and used the resulting fit to estimate ETA (Figure 3). On average, MJ-estimated ETAs for below-DT redirected reaches undershot the true arrival time by 0.13s, while those above DT undershot by 0.45s. Such errors ($\approx$33% of average reach time (1.34s) for above-DT) could negatively impact the performance of encountered-type haptic systems which rely on estimates of user trajectory and arrival for accurate positioning.

This work presents results from an initial study evaluating the Minimum Jerk (MJ) model for redirected reach. These results highlight a deviation from MJ-modeled trajectories during redirected reach, particularly for large redirection (above users' DT). Future work will investigate how to compensate for redirection in motion modeling, and explore the use of these modified models to enable immersive, redirected dynamic haptic systems.

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