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Assessing Goal-Directed Three-Dimensional Movements in a Virtual Reality Block Design Task

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***Abstract*—This study investigated three-dimensional (3D) goal-directed movements in a virtual reality (VR) simulation of a standardized psychomotor control task. Movement trajectories were collected from 22 subjects and parsed based on an existing two-phase model of motor control including ballistic and correction phases. Kinematic measures were also acquired to provide further insight into motor skill learning. Results revealed kinematic measures of total numbers of submovements and numbers of submovements in the correction phase to be significantly correlated with psychomotor task scores. A predictive model applied to the 3D movements revealed the correction phase movements to be more predictive of psychomotor performance than the ballistic phase. Findings indicate a greater degree of fine motor skill was required for performance of the psychomotor control task. This research supports the use of high resolution kinematic measures as reliable predictors of psychomotor task performance.**

Virtual reality; submovement structure; cursor trajectory; block design task; motor learning

I. INTRODUCTION

Human motor control is often investigated through measures of simplified movements in controlled scenarios, such as pointing and target acquisition tasks. In these investigations, participants coordinate movements to hit synthetic targets depicted by different stimuli. For years, such movement studies have been used in the field of Human-Computer Interaction (HCI) as a basis for improving input device and display design to benefit user performance. This is particularly true for Graphical User Interfaces (GUI), which allow novice users to interact with computer systems through direct manipulation of screen objects instead of typing complex commands. The most common GUI interaction is to move and point a cursor at a graphical object using a control device. A number of studies have evaluated HCI techniques or devices by investigating user movement characteristics while performing basic tasks such as cursor control or selection [1, 2].

Investigating *goal-directed movements*, or rapid aiming movements to a target, can also be used as a means for advancing clinical evaluation of motor impairment. For instance, [3] used established mathematical models of human motion, such as Fitts' Law [4], to examine reaching task movements of stroke patients. Results revealed the models to identify increases in time and noise in movements by patients with a history of stroke vs. healthy individuals. Currently, subjective tools like the Fugl-Meyer Assessment (FMA) [5] are used in clinical settings for evaluating levels of impairment due to stroke. Although the FMA is a well-designed and efficient clinical examination method [3], its results are entirely subjective. Recent advances in robot technology have allowed for highly detailed kinematic analyses to supplement assessment tests like the FMA by providing meaningful quantitative measures of motor performance [6, 7]. For example, [8] had stroke patients perform a number of point-to-point movements with the MIT-MANUS robotic therapy aid [6] and assessed patient FMA scores along with kinematic data. The researchers investigated changes in submovement characteristics (e.g., number of submovements) and demonstrated that movement smoothness tends to increase over time during stroke recovery. Such insight into patient movement behavior is not possible with FMA scores alone.

Objective studies of human movement generally follow two general approaches [9]. One approach is to evaluate *overall movement* characteristics through general measures such as total task time or difficulty. Fitts' Law, for instance, has been applied by HCI researchers primarily as a predictive model of time and throughput [10]. The second approach assumes that an overall movement consists of several *submovements*, which may reveal more specific information about the quality of the overall movement [11]. Woodworth [12] developed an early submovement model for goal-directed aiming movements consisting of two components, including *ballistic* and *correction* phases. The ballistic phase is relatively fast and intended to reach the general area of the target quickly. The correction phase begins when the velocity of motion to the target decreases and visual information on the current positions of the target and limb is used to make movement adjustments in order to contact the target. This model accounts for individual strategy as well as the speed-accuracy tradeoff of goal-directed movement. Even though both the overall and submovement approaches have been widely used and proven to be helpful methodologies in HCI research [2], goal-directed movements have rarely been studied as a basis for empirically assessing motor learning.

The objective of the present study was to determine the extent to which kinematic analyses complement standardized psychomotor test scores and to identify specific analyses providing the greatest explanation of task motor performance. Cursor movements used while performing a virtual reality (VR) reproduction of a psychomotor test were analyzed according to their submovements. Test scoring was performed

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based on established protocols. During performance, movements were broken down into smaller measureable components and movement characteristics were quantified as a measure of overall motor performance and compared with psychomotor test scores.

II. Goal-directed Movement

A. Overall Movement Characteristics

Fitts' Law [4] is a widely-known approach to the analysis of movement, which mathematically models the relationship among the time to move to a target, the distance from the starting point to the target, and the width of the target. Although the model is based only on two task variables, it has been identified as one of the most robust models to emerge from experimental psychology [2]. Since its inception, Fitts' Law has been validated to describe discrete movement performance in many domains, including graphical computer interface design [13], and computer input/control system development [14].

Fitts' Law can be applied to accurately predict movement between a starting point and a target, but it provides little insight into the factors that account for variability during an overall movement. This contention is supported by [1], who described Fitts' Law as a gross measure (one outcome per test), not providing detail on the movement during a trial. For this reason, other research [9] had identified a need to develop additional measures that account for variations in goal-directed movements as a function of time.

B. Submovement Structure

The existence of submovements has been supported by a wide range of research since Woodworth's classic study suggested aiming movements are composed of multiple phases. For example, [15] found that the ballistic movement phase had little dependence on the size of a target; however, the shape of the velocity profile during the correction phase became increasingly variable with a decrease in target size. The observation that the ballistic phase of accurate movements is highly consistent was confirmed by [16]. Regarding the correction phase, [17] found that multiple corrections occurred during goal-directed movement. This multiple-submovement model was supported by [18], who confirmed that about 80% of all aimed movements were composed of more than two submovements.

While there has been extensive research describing target acquisition movements, the tasks selected for these studies have primarily been repeated trials of artificial point-to-point target acquisition tasks [9, 19]. Alternatively, existing psychomotor tasks, including the Purdue Pegboard Test [20], the Minnesota Manual Dexterity Test [21] and the Block Design (BD) test [22] feature a target acquisition component, but also have been validated for use in applied settings such as physical therapy, occupational therapy, vocational evaluation and employment screening [21]. The novelty of the present work is in the detailed analysis of target acquisition movements in a VR simulation of a standardized psychomotor task. A standardized psychomotor task performance score (beyond existing normative data interpretations) may provide additional insights for interpreting aspects of submovements. Moreover, high resolution kinematic measures of submovements performed during psychomotor testing could supplement test performance scores by evaluating visuospatial and motor skills. Therefore, there is motivation to investigate kinematic analyses of goal-directed movements in standardized psychomotor tasks that have been validated as measures of human performance, like the BD test [23].

III. Block Design Test

The BD subtest from the Wechsler Adult Intelligence Scale (WAIS) [22] is a popular means of assessing visuospatial and motor skills in both research and clinical settings. In the BD task (See Fig. 1, left), participants are presented with a set of four or nine identical red and white blocks printed with either solid or cross-sectional patterns on each side. They are asked to replicate complex designs shown in a series of test cards. Scoring is measured based on speed of pattern reproduction and accuracy in placement of blocks as well as the orientation of the entire pattern. Four points are awarded for each completed design, and up to three bonus points are awarded based on completion time. The BD test is generally administered as part of a test battery, but alone it is also considered an accurate measure of spatial ability and indicates intellectual potential [22, 24].

Research has been conducted on the use of haptic-VR simulation for motor skill training with augmented visual and haptic aiding [25, 26]. The target context for these studies was skill training for persons attempting to recover from minor Traumatic Brain Injury (mTBI) or seeking to develop new motor skills for work and societal activities. The authors developed VR versions of two standardized commercial psychomotor tests, including the BD test. Unimpaired participants received motor skill training through repeated BD test trials. In addition to calculating the standard composite speed and accuracy score at the end of each completed design, the VR simulation collected detailed time and position data on each block throughout the test. The real-time performance data could be used to recreate participant movement trajectories for analysis, providing an advantage of the VR platform for motor learning research over the native test.

Figure 1. BD task (left: native, right: VR reproduction)

The capability of a VR system to capture high resolution kinematic data further motivates investigation of kinematic measures of the BD test to provide learning insights beyond existing scoring interpretations. It was expected that an analysis at the submovement level could provide details on learning beyond overall movement measurements. To address the objective of the study, a VR simulation of the BD task was

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developed to collect kinematic data and test scores as part of motor skill assessment. Following development, a preliminary study was performed to determine how submovement data varied with standardized scoring techniques. The general approach was to: (a) parse participant goal-directed movements during BD task training into ballistic and correction phases; (b) determine kinematic measures for each phase; and (c) compare the kinematic responses with standardized composite test scores. Repeated BD training trials were conducted for these purposes. In general, it was expected that the higher resolution measures of human motor skill could improve the accuracy and strengthen the predictive utility of existing models of motor performance. If integrated in rehabilitation programs, such models could support identification of more effective therapies and potentially faster and more complete recovery of motor skill.

IV. METHODOLOGY

A. Paticipants

Twenty-four participants between the ages of 18 and 44 were recruited for the study. All participants were required to be right-hand dominant and have 20/20 vision. Right-hand dominance was identified through a demographic questionnaire and confirmed using the Edinburgh Handedness Inventory [27]. Participants were required to complete the BD task using their non-dominant (left) hand in order to simulate a minor motor impairment and to provide the opportunity for participant motor learning through task performance.

B. Apparatus

The VR interface for the BD task (see Fig. 2) was presented on a PC integrated with a stereoscopic display using a NVIDIA® 3D Vision™ Kit, including 3D goggles and an emitter. The interface recorded participant performance data automatically. A SensAble Technologies PHANTOM Omni® haptic device was used as the control interface. The Omni includes a boom-mounted stylus that provides 6 degrees of freedom (DOF) for movement and 3 DOF in force feedback.

The software developed for the study included a visually realistic simulation of the BD subtest from the Wechsler Abbreviated Scale for Intelligence (WASI) [23]. The virtual environment (VE) features included a virtual tabletop with three parts (see Fig. 3): (a) a display area showing the design model copied by the participant, (b) a work area used for arranging the blocks; and (c) a target area consisting of a 2x2 or 3x3 (depending on the size of the model) square grid where participants assembled their designs. The Omni haptic device was used to manipulate a cursor appearing on the display. Participants could touch the cursor to a block and press a button on the stylus to "grab" the block. The blocks could then be lifted from the table's surface and rotated along any axis using the stylus. Blocks could be moved around the display with the Omni and placed in desired positions within the target area. Participants would move and rotate each block into the target grid until the model was fully assembled. All cursor and block positions were recorded automatically in real-time (every 100 ms) in x, y and z coordinates in the VE.

Figure 2. VE setup

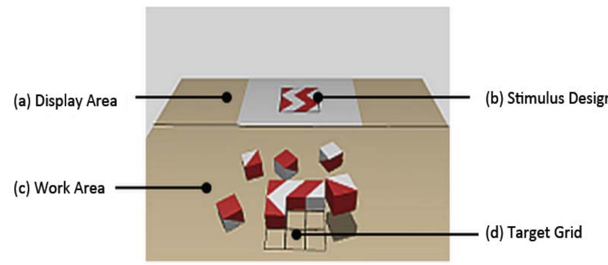

Figure 3. VE layout

C. Procedure

All participants were introduced to the haptic device and received instruction on how to manipulate objects in the VE. Participants were permitted to use the haptic device until they felt comfortable (by verbal verification). Participants were also required to perform multiple trials of a simple pilot task incorporating block movements and rotations to ensure familiarity with the haptic device.

Each participant visited the research lab for three consecutive days in which they completed eight BD test trials, including 10 designs per trial. The combined duration of the training sessions was approximately 3 hours.

D. Movement Trajectory Data

Movements in the BD task can be categorized as cursor movements or block movements. *Cursor* movements were required for navigating to blocks at the beginning of a trial and after placing a block. No rotations were required during cursor movements. In this study, movements between grasping and releasing a block at the target grid and grasping another block were assumed to be goal-directed movements since they required rapid aiming movements. Detailed kinematic data on these movements were collected for analysis. *Block* movements included repeated grasping, moving, positioning and placement relative to other blocks to replicate various designs. These movements were made rapidly and inconsistently and, therefore, were not considered to be goal-directed. More complex movements requiring motor planning and rotational wrist movements were not assessed in this study.

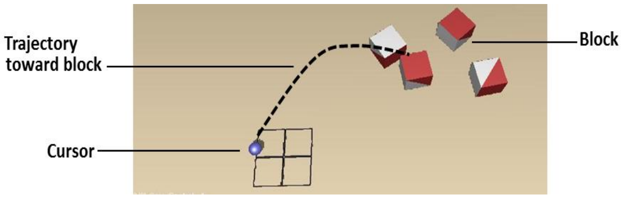

Figure 4. Goal-directed movement in BD task

Goal-directed movements were identified based on: (a) the cursor's starting point relative to the blocks; (b) whether a block was grasped during the movement; and (c) grasping actions performed at the ending point of the movement. The goal-directed movements were extracted from the trajectory (x, y and z) data points.

E. *Parsing Movement*

During the analysis of pilot data, it was observed that hesitation by novice users of the haptic device or unnecessary movement during searching and planning tended to confound the movement data. Thus, movements of more than 10 sec or less than 1 sec were excluded from the test data in order to exclude planning and/or random behaviors from the analysis. In addition, to minimize noise from normal user tremors evident through the Omni haptic device, the data were smoothed with a 2^{nd} order Butterworth low-pass filter with a 3Hz cut-off.

The criteria for parsing the overall movement data into ballistic and correction phases were based on [28] and [9]'s definitions of goal-directed movements and component submovements. Latency and verification phases, in which no significant movement occurred, were also identified and removed. Movements in which the speed of the cursor remained below 5% of the overall peak movement speed were identified as *pauses*. Submovements were defined as the movements occurring in between the pauses. Additional processing was performed to avoid erroneously identifying small involuntary tremors or signal noise from the Omni haptic device as submovements. First, a minimum submovement duration of 200ms was identified. Second, peak velocities for submovements were required to exceed 10% of the peak velocity of the overall movement. If movement intervals did not meet these additional requirements, they were combined with an adjacent submovement. If the last submovement did not meet the requirements, it was removed from the analysis. The first submovement was recognized as the overall movement's ballistic phase unless it constituted less than 25% of the total path length. If the submovement did not meet these criteria, the next adjacent submovement was included in the phase.

F. *Variables and Hypotheses*

Several dependent variables (DV) were recorded by the software during all BD tests (trials):

- *BD error*. Calculated by subtracting a participant's actual score from the maximum possible test score (i.e., 71 points)
- *Overall Submovements (OS)* - The number of submovements in an overall movement
- *Ballistic Submovements (BS)* - The number of submovements in a ballistic phase
- *Correction Submovements* (*CS)* - The number of submovements in a correction phase
- *Ballistic Velocity* (BV) - Mean velocity for a ballistic phase
- *Correction Velocity* (CV) - Mean velocity for a correction phase

All DVs were normalized (as Z-scores) to account for individual differences by considered average individual performance and variance across all test trials.

The analyses of the present study assessed relationships between the kinematic response measures and the BD test score. Since BD scoring is based on speed and accuracy, it was hypothesized that faster and smoother movements would produce higher scores. The number of BD errors was expected to decrease with increases in velocity and increase with higher numbers of submovements in both phases (ballistic and correction; Hypothesis (H)1). Furthermore, based on the characteristics of movements in the ballistic and correction phases, it was expected that kinematic measures on the correction phase would be more highly correlated with the BD score than measures on the ballistic phase (H2). In addition, kinematic measures in the correction phase were expected to explain more of the BD score variance than in the ballistic phase (H3).

V. RESULTS

Among the 24 subjects, data from two subjects resulted in no improvements in BD scores (i.e., the BD scores were the same across all eight subsequent trials). Therefore, the data from these participants were excluded from the analysis, and the total number of response observations was 176 (22 participants times 8 trials).

The correlation analyses relating BD scores to kinematic measures are presented in Table 1. Pearson product moment correlation coefficients (r-values) were calculated in order to identify any significant relationships between the kinematic measures and BD scores. BD error was correlated most highly with *Overall Submovements* ($r = 0.56$, $p < 0.0001$) as compared with the other kinematic measures. *Correction Submovements* was also significantly correlated with the BD error ($r = 0.51$, $p < 0.0001$). However, BD error was only moderately correlated with *Correction Velocity* ($r = -0.43$, $p < 0.0001$) and *Ballistic Submovements* ($r = 0.31$, $p < 0.0001$) and weakly correlated with *Ballistic Velocity* ($r = -0.22$, $p = 0.01$). That is to say, the kinematic measures varied differently relative to the comprehensive test score.

Regression analyses were performed in addition to the correlation analyses in order to evaluate the degree to which the kinematic measures explained BD scores. Separate analyses were conducted for the ballistic and correction phases due to differences in the nature of submovements. In each analysis, the response was BD error while the submovement and movement velocity measures represented predictors. The regression models were structured as:

$$BD\ error = \beta_0 + \beta_1 \cdot BS + \beta_2 \cdot BV + \varepsilon \quad \text{(Ballistic)} \qquad (1)$$

$$BD\ error = \beta_0 + \beta_1 \cdot CS + \beta_2 \cdot CV + \varepsilon \quad \text{(Correction)} \qquad (2)$$

Estimates of intercepts and slopes, based on a general linear model fit to the data for each phase, are presented in Table 2. As might have been expected based on the correlation analyses, all parameters were significant in predicting BD scores for both phases ($p < 0.0001$). For each phase, as the number of submovements increased or the velocity of movements decreased, the BD error increased (i.e., BD score decreased). In other words, smoother and faster movements resulted in increased psychomotor performance scores. In terms of predictive power (r^2), a model including kinematic measures on the correction phase ($r^2 = 0.335$) explained a greater proportion of the variance in the BD score than measures on the ballistic phase ($r^2 = 0.132$). Since all variables were normalized (as Z-scores), the intercepts (β_0) of both models were zero.

These results imply that the submovement variables (*Ballistic Submovements* and *Correction Submovements*) affect BD error more than the velocity variables (*Ballistic Velocity* and *Correction Velocity*) in each model because the absolute values of estimated submovement coefficients were larger than the velocity coefficients.

TABLE I. CORRELATION ANALYSIS OF BD ERROR AND KINEMATIC MEASURES OF GOAL-DIRECTED MOVEMENTS (N= 176)

	Submovements			***Velocity***	
	Overall	***Ballistic***	***Correction***	***Ballistic***	***Correction***
r (with BD error)	0.56	0.31	0.51	-0.22	-0.43
p-value	<.0001*	<.0001*	<.0001*	0.01	<.0001*

*significant at the α = 0.05 level.

TABLE II. SUMMARY OF MULTIPLE REGRESSION ANALYSES ON BOTH PHASES

Ballistic Phase					
Source	***DF***	***Sum of Squares***	***Mean Square***	***F Ratio***	***Prob > F***
Model	2	20.43	10.2157	13.23	<.0001*
Error	173	133.568	0.7721		
Total	175	154			
T-test on Parameter Estimates					
Variable		***Estimate***	***Std Error***	***t Ratio***	***Prob>|t|***
BS		0.29364	0.07123	4.12	<.0001*
BV		-0.18594	0.07123	-2.61	0.0098

Correction Phase					
Source	***DF***	***Sum of Squares***	***Mean Square***	***F Ratio***	***Prob > F***
Model	2	51.65542	25.8277	43.65	<.0001*
Error	173	102.34458	0.5916		
Total	175	154			
T-test on Parameter Estimates					
Variable		***Estimate***	***Std Error***	***t Ratio***	***Prob>|t|***
CS		0.41450	0.06566	6.31	<.0001*
CV		-0.29019	0.06566	-4.42	0.0098

VI. DISCUSSION

Results revealed that some of the kinematic measures, including *Overall Submovements* and *Correction Submovements*, were significantly correlated with BD scores (in partial support of H1). The finding of a relationship between the number of overall submovements and motor skill proficiency is consistent with the results obtained by [8]. In general, smoothness increased (i.e., the number of submovements decreased) during training. Except for *Ballistic Velocity*, all other measures were at least marginally correlated with the BD score.

The kinematic measures on the correction phase were more highly correlated with BD scores than those on the ballistic phase, supporting H2. This may be because *Ballistic Submovements* tended to reduce to a single movement midway through the training trials and, therefore, ceased to decrease due to a floor effect. However, BD scores continued to increase. *Correction Submovements*, in contrast, kept decreasing throughout trials. This suggests that BD task performance is more dependent on fine motor skill, since the kinematic measures on the correction phase yielded higher correlations with the comprehensive score than those on the ballistic phase. Moreover, the VE dimensions may not have been large enough to make the ballistic phase a critical phase to the overall movements.

In general, the lack of perfect correlations among any of the kinematic measures with the psychomotor task scores may be interpreted as each kinematic measure accounting for specific aspects of performance. Measures on the ballistic and correction phases may describe gross and fine motor skills, respectively. In addition, since the BD task score accounts for both speed and accuracy, some additional kinematic measures that are relevant to accuracy, such as the number of target overshoots or path length (trajectory efficiency), may provide a more complete explanation of that aspect of motor task performance.

Hypothesis 3 was supported by the fact that a predictive model in kinematic parameters for the correction phase had a higher coefficient of determination (R^2) than a model with parameters on the ballistic phase. This implies that kinematic measures on the correction phase may be more predictive of the comprehensive test score. Accordingly, it may be possible to measure visuospatial and motor skills by analyzing kinematic measures on partial movements in a correction phase instead of using an elaborate standardized psychomotor test. Although there are no absolute criteria for good R^2 values, it can generally be expected that adding visuospatial parameters would improve the reliability of the predictive model, as traditional BD scores are influenced by both visual-spatial ability and motor skills.

VII. CONCLUSION

This study demonstrated an assessment of goal-directed movement in a VR simulation of the BD task for training motor skills through an analysis of submovment data. The kinematic data were generated in real-time by a VR simulator and subsequently parsed into performance measures. The study also presented a high-resolution data analysis of standardized psychomotor test performance by healthy participants. Furthermore, the study identified differences in motor skill assessment based on ballistic and correction phase submovements. Statistical analysis revealed that some kinematic measures are highly correlated with standardized psychomotor test scores and are significant predictor of block design behavior. The correction phase of motion appears to be more predictive of visuospatial and motor skill performance. Finally, the results are noteworthy because the analysis and assessment were based on a standardized psychomotor task rather than a unique empirical task. Given that this is preliminary research, future work should investigate additional measures such as peak acceleration and deceleration of movements [29] for characterizing learning or predicting motor skill performance. In addition, much more complicated movements will be studied and assessed, such as block grasping or rotation in the BD task, or other psychometric tests.

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