Human-Machine Interface Degree of Freedom Effects on Performance in Space Telerobotics

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INTRODUCTION: There are many potential human-machine interfaces for controlling complex robotics. However, restrictions in hardware, software, or human capability may pose limits on the input device degrees-of-freedom (DOF). This study examined effects on operational performance and strategy when interface DOF were limited, hypothesizing that different limitations on interface DOF would affect operator performance and technique.

METHODS: Experiments used a Canadarm2 simulator with a dual-joystick interface adapted to operate under limited DOF conditions. Four interfaces were compared: full multiaxis (FM), limited translation (TL), limited rotation (RL), and without simultaneous translation/rotation or "non-bimanual" (NB). Subjects were tasked with operating the Canadarm2 in a simulated ISS control scenario to approach and grapple a moving cargo vehicle within a 90-s time limit.

RESULTS: No significant difference was seen between FM and RL in task time or grapple success, and both were significantly different from TL. NB exhibited significantly increased task time from FM and RL, but no significant difference in grapple success rate. When rotating, subjects decreased time spent using multirotation for NB over FM.

DISCUSSION: Similar performance between FM and RL suggests that restricting rotation may be preferred for interfaces with DOF design limits. For the NB condition, there was increased task time combined with decreased multirotation, highlighting potential use for NB in training for rotation efficiency. Two different strategies were observed during TL to overcome inability to visually track, align with, and move toward the target simultaneously. Examination of these techniques provides insight on which strategic elements were most critical for success.

KEYWORDS: human-robot interaction, control interfaces.

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Human-robot control interface designs cannot always have the same degrees of freedom (DOF) as the system they are controlling, or the environment in which they operate. Due to factors such as hardware limitations, mass or cost considerations, or other requirements, a control interface may have fewer DOF than either the robot or its environment. However, no investigation has been conducted specifically on the characterization of control interfaces that allow multiple inputs while limiting operational DOF.

Past control interface design studies for operation in 6 DOF environments (with full three-dimensional motion along the 3 translational and 3 rotational axes) have focused on the use of 6 DOF control systems.[4,19,20] For example, in reviewing potential interfaces for telerobots entering hazardous environments, Fischer[4] only considered 6 DOF device controllers. Similarly, Zhai assumed 6 DOF interfaces would be required for experiments on control systems in 6 DOF environments[20] or 3 DOF interfaces where the environment called for translational motion only (effectively a 3 DOF environment).[19] However, existing interfaces for complex equipment (e.g., cranes, surgical robots) reveal cases of lower DOF interfaces used in operation through 6 DOF space. Surgical robotic arms with 4 DOF (utilizing two-DOF shoulder and two-DOF elbow joints) have used master-slave style interfaces, for which robot motion is meant to mimic the operator's hand placement and orientation.[18] Controlling the robot endpoint with such devices creates

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a feeling of 6 DOF interface control for the surgeon. In construction, backhoes are 4 DOF arm-like systems in which both traditional and experimental control schemes use 4 DOF interfaces to maneuver through 6 DOF space.[9,10] Crane operation involves a variety of input systems, typically with 4 DOF interfaces using a combination of joystick and lever, button, or foot controls.[12] Studies have shown that in multidirectional tasks the use of multiple inputs provides advantages over a purely single input (one action at a time) interface.[7,19] While it is intuitive to design multi-input interfaces to have the same DOF as either the machine in use or the operating environment, it is not always feasible.

The Canadarm2, or Space Station Remote Manipulator System (SSRMS), is a 7 DOF robotic arm, with 3 joints at the shoulder, 1 joint at the elbow, and 3 joints at the wrist. Using these degrees of freedom, the endpoint of the arm can move through 6 DOF space (translation and rotation about all 3 Cartesian axes of the endpoint). The SSRMS is controlled through a dual-joystick interface. Each joystck controls 3 DOF of the endpoint, with the left hand commanding translation and the right rotation, for a combined 6 DOF interface. This multi-input system provides additional challenges as it requires bimanual control, thus artificially separating the 6 DOF space. In a previous study,[7] a wearable gesture control interface using surface electromyography (sEMG) and inertial measurement unit (IMU) sensors was designed to examine unimanual control of the SSRMS. Gesture-to-command mappings for the fully-wearable interface were compared with the traditional SSRMS dual-joystick interface. While the goal of the gesture controller was to have multi-input control, the implementation of the sEMG signals required inputs mapped from these signals to be made one at a time.[7,16,17] Thus, any aspect of control (e.g., rotation, translation) mapped from the sEMG signal (as opposed to the IMU signals) would be reduced to single DOF inputs. It was unclear how selecting which signals mapped from the sEMG would impact operation in a 6 DOF environment.

The effects of limiting interface DOF for operation with higher DOF robots and environments are unknown. This study examines how control interfaces with DOF reductions affect performance compared to full 6 DOF systems, and if specific DOF reductions have greater impact (positively or negatively) on operation. To examine these questions, the SSRMS was used as a robotic case-study in a virtual International Space Station (ISS) environment.[6,11,15] While it was not possible to add further DOF to the experimental gesture system, we could selectively limit different DOF on the traditional robotic arm controllers in order to compare reduced and full DOF conditions using a single interface. Using the joystick control interface, different input combinations could be prevented from commanding the robot arm, allowing selective limitation of different interface DOF.

There are three types of multiaxis operation that may be considered in a 6 DOF environment: multitranslation (motion along more than one translation axis), multirotation (motion about more than one rotation axis), and combined rotation/translation (motion along a translation axis and about a rotation axis simultaneously). This study examined the effects of removing different multiaxis capabilities from the control interface. That is, interface DOF were reduced to either four DOF, or two nonconcurrent three DOF interfaces, depending on which type of multiaxis motion was limited. A human study was conducted, with different types of interface DOF limitations. We hypothesized: 1) that limiting controller DOF would change user performance and workload, and 2) that operations with limited controller DOF would affect overall technique and multiaxis use in nonlimited directions.

By testing an interface with differently limited DOF in operation of a 6 DOF system, the work sought to understand how these limitations affect performance, workload, and technique. In doing so, this research provides insight for future interface design on which DOF are necessary for efficient user performance, and which, if excluded, would impact system operation.

METHODS

Subjects

The study protocol was approved in advance by the MIT Committee on the Use of Humans as Experimental Subjects. Subjects provided written informed consent and were compensated for their time. There were 21 subjects, 1 of whom was disqualified from completing the study, leaving 20 tested subjects. There were 13 men and 7 women between ages 21 and 35 (M = 25.5, SD= 3.64 yr). Of the test subjects, 19 were right hand dominant. Subjects were included provided they had self-reported no injury or pathology affecting hand function, and self-reported visual ability to clearly distinguish all elements of the display. Additional screening occurred during the study procedure, in which subjects unable to complete 3 of 10 practice trials for each test case were disqualified from continuing with the experiment. The one excluded test subject mentioned previously was disqualified in this manner.

Equipment and Materials

The study used an SSRMS simulator[6,11,15] with the traditional SSRMS dual-controller interface operated in a rate-controlled configuration (i.e., command inputs specified end-effector velocity). The simulator environment was constructed using Vizard V virtual reality software (Santa Barbara, CA). The hardware included three monitors displaying different views of a modeled ISS, representing fixed exterior camera feeds. The virtual SSRMS had three structural segments connected by joints, often compared to a human arm structure. Motion was controlled at the end-effector, or "hand" segment at the end of the arm using a two-joystick interface similar to operation on station (**Fig. 1**). The left joystick, translational hand controller (THC), controls translation. The right joystick, rotational hand controller (RHC), controls rotation and includes the grapple trigger (permitting capture of cargo) and message response button. The input axes were as indicated in Fig. 1C. The simulator was augmented for this study to permit the altered DOF test conditions.

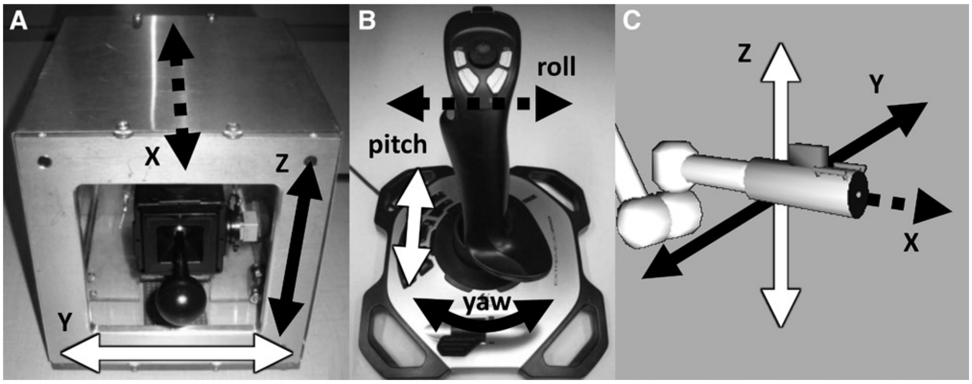

Fig. 1. Standard joystick interface. A) Translational (left hand) joystick; B) rotational (right hand) joystick (grapple trigger on reverse side); and C) reference axes of control inputs at the end-effector.

The experimental tasks performed for this study were Track and Capture trials, where subjects had 90 s to grapple a simulated H-II Transfer Vehicle (HTV) cargo vehicle target in free drift. The center screen of the simulator displayed a view from the end-effector camera with a set of green crosshairs and guidelines overlaid. The display was configured as an inside-out display, where the crosshairs were fixed and the image of the world was moving. To successfully grapple a target, subjects had to be close enough to the grapple pin on the HTV such that their outer guidelines were within the white target line on the grapple pin and aligned with the crosshairs centered in the white target circle (**Fig. 2**). The end-effector also had to be oriented such that it was within 5° of perpendicular to the target surface using the white ball on the target pin for guidance, with the white target bar horizontal.

A total of four input conditions were tested: full multiaxis (FM), translation limited (TL), rotation limited (RL), and nonbimanual (NB). The nominal joystick configuration was presented to subjects as "full multi-axis" to prevent bias. FM allowed standard control of the SSRMS along multiple axes in any combination. The TL condition allowed subjects to translate along only one axis at a time. If they attempted to move the THC to input multiple directions, the SSRMS would stop all translation. In TL, the RHC operated along multiple axes and could be used simultaneously with the THC. In contrast, the RL condition allowed rotational motion along only one axis at a time, while the THC allowed multiple inputs and both controllers could be used simultaneously. The NB condition allowed normal multiaxis inputs in both rotation and translation individually, but the THC and RHC could not be operated in tandem. If subjects attempted to apply input from both controllers, no input would be registered to the SSRMS simulator and no motion would occur.

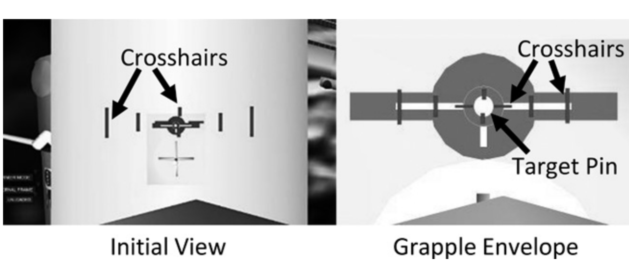

Fig. 2. View of target from the end-effector view A) at the start of a trial and B) with crosshairs aligned for grapple.

All task performance data were collected through the SSRMS simulator. The dependent measures of interest for the first hypothesis included average trial time, grapple success rate, and distance to target at time of failure. Workload measures included an objective measure and a subjective measure. The objective workload measure was average response time for a secondary task described in the protocol, transformed as the inverse of average response time for analysis. Subjective workload was measured using the NASA Task Learning Index (TLX) survey.[8] All previously described measures were pertinent to hypothesis two. Additional performance metrics used to assess technique in analysis of hypothesis two included multitranslation time, multirotation time, bimanual operation time, percent multitranslation (of time spent translating), percent multirotation (of time spent rotating), and percent bimanual operation. Two additional metrics ("against-goal rotation" and motion in the x-axis direction) were used to quantify strategy for the TL trials and were motivated by observations of the TL trials during data collection. While we present the metric and strategy definitions in this section, the frequencies of these strategies within the TL trials are presented in the results section.

Standard Track and Capture strategy involves combining three elements: 1) visual tracking of the grapple pin, keeping it in view of the end-effector camera; 2) closing the distance to the target vehicle; and 3) aligning the end-effector with respect to the grapple pin to maintain the required orientation grapple. The approach then follows a smooth path such as that shown in **Fig. 3A**. In the TL condition, with only one translational motion permitted at a time, it is no longer possible to execute all three of these elements throughout the approach to the target. Instead, two alternative strategies emerge under the TL condition (**Figs. 3B and C**).

For the first strategy (Fig. 3B), referred to as "translational-anticipate-and-wait," subjects focus on closing the distance and aligning the end-effector (components "2" and "3" of full tracking), while sacrificing the direct visual tracking element. In this strategy, subjects project where the target will move along the y and z axes, then orient themselves with proper translational alignment using lateral and vertical movements ahead of the anticipated motion. They then close in the distance in the x direction as the target drifts toward the anticipated lateral and vertical position, waiting for the target to arrive at the projected location. Orientation adjustments with rotation are performed simultaneously throughout this process. In the other strategy (Fig. 3C), "end-effector steering" strategy, subjects use components "1" and "2" of the complete tracking strategy, sacrificing

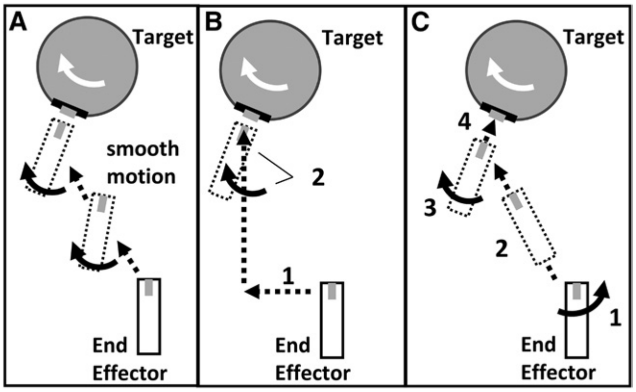

Fig. 3. 2D example of motion pattern: A) normal tracking technique; B) "translational-anticipate-and-wait" strategy; and C) following "end-effector steering" strategy.

alignment to maintain visual of the target and close distance with forward (x-axis) input at an angle. This involves the subject rotating opposite the direction needed for alignment and steering the end-effector toward the target without use of lateral or vertical translations. The time spent (or percentage of trial) moving against expected alignment directions became the first strategy metric, known as "against-goal rotation." The second metric used to define strategy quantitatively was motion along the x-axis (forward input, Fig. 1C), measured as either time spent or percentage of trial using x-axis motion.

Procedure

Upon providing consent to participate in the study, subjects answered questions on basic demographic information and completed the Vandenberg and Kuse Mental Rotation Test (MRT) for special skills assessment.[14]

Subjects were trained on the SSRMS Simulator using a PowerPoint guide. Following a description of the SSRMS and simulator system, subjects were instructed how to control translation and rotation in the FM condition and were provided with some brief practice with the controllers. To begin this introductory period, subjects operated each joystick separately in the "neutral" simulator environment (SSRMS positioned behind the space station truss, with no targets or other added objects). Then they were given a series of three static targets to approach using the FM condition to become accustomed to the joysticks and environment. This introduction also provided an opportunity to describe the experiment side-task, which consisted of pressing a button on the right joystick every time the word "message" appeared on the simulator center screen.

The four different test conditions were introduced, and subjects were asked to complete a series of Track and Capture tasks (**Table I**). For each condition, subjects would perform 4 practice trials, a readiness test consisting of 10 trials, and 13 experimental trials, then move on to the next condition (a total of 27 trials per condition). After each interface condition, subjects completed the NASA TLX. For the practice trials, subjects were given two trials where the target drifted in two translational directions (without rotation), followed by two trials where the target drifted with one rotational and one translational direction. The number of target translation and rotation drift directions for a given trial was defined as the drift type. The readiness test consisted of 10 Track and Capture trials, which served as both practice and a means of determining if subjects fully understood the task and techniques for controller operation. Readiness test trials all had the same drift type, consisting of one translational and one rotational direction. Subjects needed to successfully complete 3 of the 10 trials to pass the readiness test and continue. If a subject did not pass the readiness test during a test condition, they were considered not trained, or unable to reliably complete the experimental trials with competency and were ineligible to continue with the study.

Upon completion of the practice trials, subjects completed 13 additional Track and Capture trials, each with a mix of translational and rotational drift (Table I). Subjects were told to complete each trial with the following priorities: 1) grapple success and completion speed, and 2) answering messages. The 13 trials were randomized into 4 orders, with an order assigned to a specific test condition such that each subject faced the same trial order for each condition regardless of condition order. This prevented subjects from learning a set trial order during the experiment. Test conditions were presented to each subject in one of two orders to allow later analysis of condition order effects. Orders used were the FM-First order (FM, NB, RL, TL) such that subjects started with no DOF limitations and different DOF were removed from there. The alternate, TL-First order followed the reverse pattern (TL, RL, NB, FM). Order was assigned based on MRT score as the assessment was completed, such that balance was maintained between the two order groups for even group size and mental rotation ability (FM-First order MRT scores: Mean = 22.5, SD = 6.2; TL-First order MRT scores: Mean = 21.9, SD = 6.92).

Statistical Analysis

Initial statistical analyses revealed that these data were nonlinear and residuals consistently failed Kolmogorov-Smirnov tests of linearity, prompting the use of nonparametric tests. Kruskal-Wallace (KW) tests were conducted with each of the dependent variables (detailed above), first with condition as the grouping variable, and again with "condition-order" as a grouping variable as a surrogate for examining interaction effects with this nonparametric method. For this second set of tests, data were grouped into 8 levels (4 condition $\times$ 2 order). If a KW test was significant, pairwise comparisons were performed following the Dwass-Steel-Chritchlow-Fligner method, which has an embedded correction for multiple comparisons.[3] Additional KW tests of the multiaxis technique variables (percent multi-translation, percent multirotation, percent bimanual operation) were conducted across drift type for each condition individually with order pooled. Although not all are reported here, a total of 30 KW tests were performed, 25 of which were significant. A level of significance correction was used to assess the multiple omnibus tests following the False Detection Rate method,[1] such that an adjusted significance level of 0.0417 was used. Within TL, trials were labeled as following the

Table I. Target Drift Types and Drift Directions Per Trial.

	TRANSLATIONAL DRIFT				ROTATIONAL DRIFT			
	Left	Away	Up	Down	Yaw Right	Pitch Away	Pitch Toward	Drift Type
Training trials								
1	X		X					2T
2	X			X				2T
3				X		X		1T-1R
4	X				X			1T-1R
Readiness test (all trials included twice)								
1	X				X			1T-1R
2			X			X		1T-1R
3				X			X	1T-1R
4				X		X		1T-1R
5			X				X	1T-1R
Experimental Trials								
1	X				X			1T-1R
2			X			X		1T-1R
3				X			X	1T-1R
4	X				X		X	1T-2R
5	X				X	X		1T-2R
6				X	X		X	1T-2R
7			X		X	X		1T-2R
8	X		X		X			2T-1R
9	X		X			X		2T-1R
10	X			X	X			2T-1R
11	X			X			X	2T-1R
12	X		X		X	X		2T-2R
13	X			X	X		X	2T-2R

"translational-anticipate-and-wait" or "end-effector steering" strategy based on absolute against-goal rotation time. Though higher use of against-goal rotation was expected for end-effector steering trials, some value of against-goal rotation was known to exist during the course of nominal operation in the FM case. Thus, the limit of against-goal rotation used to determine a trial as either translational-anticipate-and-wait or end-effector steering became the upper limit of the range of against-goal rotation time for FM trials excluding extreme values, or the upper outer fence of against-goal rotation time for the FM condition. When assessing the two TL strategies, position error for failed trials at time-out were compared across strategy via two-sample t-test, as were success rates between strategies.

RESULTS

There was a significant effect of condition-order on grapple success ($H = 237.48$, $P < 0.001$). Pairwise comparisons revealed a statistically significant difference between TL and the other conditions ($P < 0.001$ for all cases) with TL having the lowest grapple success rate (**Fig. 4**). No significant difference was found between FM and RL conditions. Grapple success was lower for TL than for NB, with both showing reduced performance in the FM-first order. Position errors at time-out for NB failed trials ($N = 18$) were compared with that of TL failed trials ($N = 92$). Mean distance from target at time-out was significantly greater in TL failures than NB failures [$t(46.7) = -1.812$, $P = 0.038$]. When position error was broken into individual axes, mean distance from target in the x (forward) direction was significantly greater in TL failures [$t(55.5) = -1.851$, $P = 0.035$]. There was no significant difference in z (up/down) or y (right/left) error between NB and TL failed trials.

A significant difference was found in average trial time for condition with order pooled ($H = 689.94$, $P < 0.001$) (Fig. 4B) with pairwise comparisons indicating no statistically significant difference from FM for RL, but significant differences between all other conditions from each other ($P < 0.001$). Significant difference was also found for average trial time across condition-order ($H = 729.94$, $P < 0.001$), with nearly all treatment levels significantly different from one another ($P < 0.001$). However, pairwise comparisons revealed no significant difference in trial time between NB trials across order, TL trials across order, between FM in order one (FM-First) and RL in order two (TL-First), or between FM in order two (TL-First) and RL in order one (FM-First).

Analysis across test conditions with order pooled showed overall effects for both NASA TLX score ($H = 543.82$, $P < 0.001$) and inverse message response time ($H = 141.44$, $P < 0.001$). However, pairwise comparisons indicated no statistically significant difference between RL and FM conditions for either workload metric ($P = 0.05$ and $P = 0.61$ for subjective and objective, respectively). From NASA TLX scores (**Fig. 5**) NB and TL each had significantly different scores than each of the other conditions ($P < 0.001$ for all cases). FM and RL had the lowest measured workload while TL held the largest, with NB falling in between. Inverse response time data supported findings from subjective workload analysis.

Multitranslation time supported an effect of condition (overall effect: $H = 54.57$, $P < 0.001$), with NB having a greater multitranslation time compared to both FM and RL (**Table II**) ($P < 0.001$). However, when considering the percentage of total translation time using multitranslation, there was no significant difference between NB and FM. There was a significant effect of interface condition for absolute multirotation time ($H = 53.46$, $P < 0.001$). Pairwise comparisons revealed larger multirotation time for TL ($P < 0.001$ for both comparisons), but no significant difference between NB and FM. Analysis on percent multirotation of time spent rotating across condition, however, did reveal significant difference between NB and FM ($P < 0.001$). Additionally, significant effects of condition on total rotation time ($H = 398.3$, $P < 0.001$) revealed TL had greater total

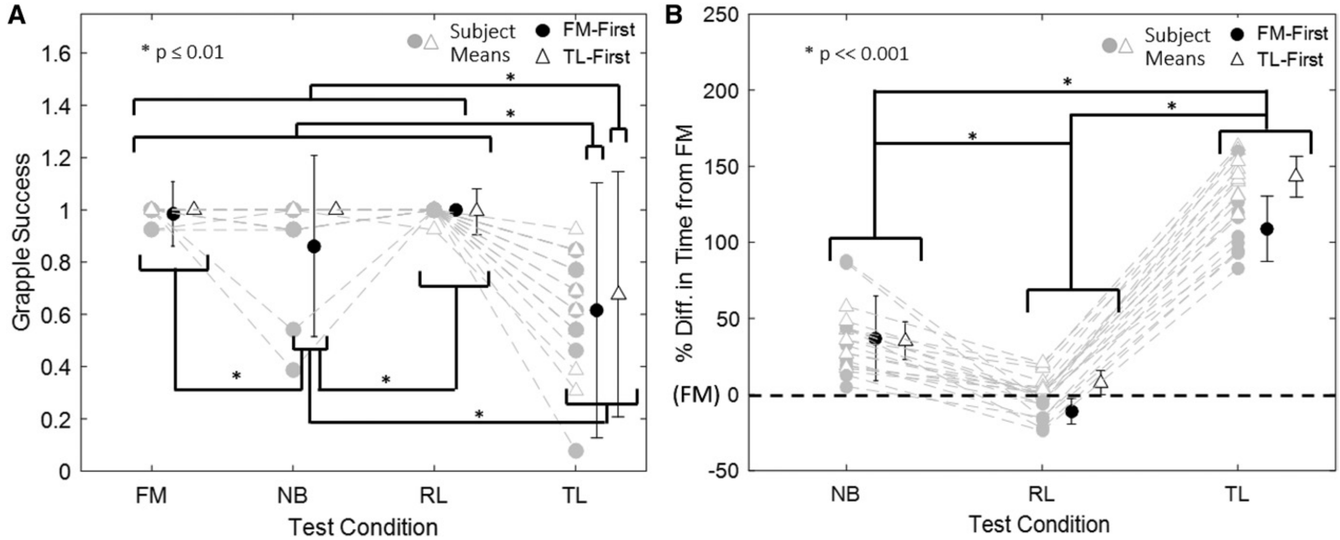

Fig. 4. A) Grapple success means by test condition. B) Percent difference in mean trial time from the FM condition. Not shown: significant difference exists between order levels for the RL condition and the TL condition. For each plot, gray markers depict individual subject means, while bold markers and error bars show overall means and standard deviations for the indicated experimental order group, respectively. Significant differences are indicated by the horizontal brackets.

rotation time than FM ($P < 0.001$) and NB had a lower total rotation time than FM ($P < 0.001$). Effect of condition on absolute bimanual time ($H = 559.701$, $P < 0.001$) found it was largest for TL and lowest for RL, with all conditions significantly different from each other ($P < 0.001$ for all cases). For percent bimanual use across condition ($H = 63.40$, $P < 0.001$), all conditions were significantly different from each other ($P \leq 0.001$ for all cases) with bimanual operation most frequent in FM and least frequent in TL.

Strategy differences with the TL condition were determined by x-axis (forward-back) motion and against-goal rotation (**Fig. 6**). All trials with x-axis motion for more than 50% of trial time were successful, and all trials with x-axis motion below 30% of total trial time were failures. The upper outer-fence for against-goal rotation time in FM trials was 18.412 s. Excluding extreme values, it was assumed that translational-anticipate-and-wait trials in TL (those not utilizing excess against-goal rotation) would have against-goal rotation times within this range. Thus, all TL trials with against-goal rotation below 18.412 s were considered as using the translational-anticipate-and-wait strategy ($N = 230$), while those trials with against-goal rotation time exceeding this value were considered as following the end-effector steering strategy ($N = 30$) (Fig. 6). The success rate of the translational-anticipate-and-wait trials was significantly greater than that of the end-effector steering trials [$t(36.3) = 2.07$, $P = 0.023$].

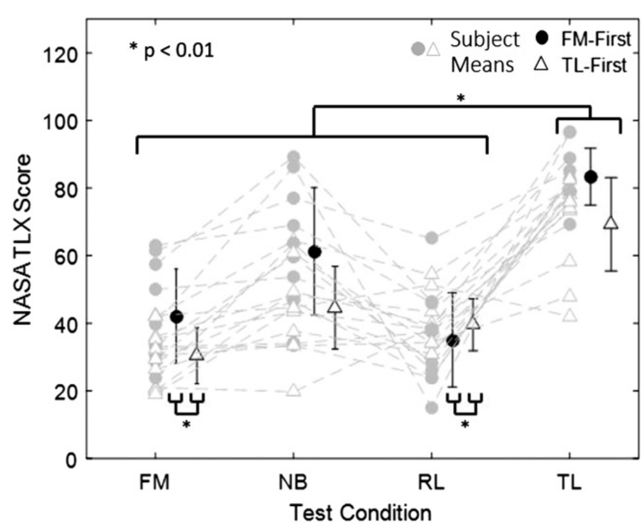

Fig. 5. NASA TLX score means by test condition. Gray markers depict individual subject means, while bold markers and error bars show overall means and standard deviations for the indicated experimental order group, respectively. Horizontal brackets indicate significant differences. Not shown: for each order, significant difference exists between the NB condition and all other conditions.

DISCUSSION

This study examined two hypotheses related to interface DOF. As specified in the introduction, the first hypothesis anticipated an effect of DOF on performance and workload effects. The second hypothesis pertained to effects of particular interface DOF configurations on operational technique (i.e., rotation limiting affecting translation, translation limiting affecting rotation, and an effect of the NB condition on technique). The first study hypothesis was supported. TL conditions limited performance and increased workload, indicating that such a set of DOF restrictions would be a poor choice in designing a control system. In the Track and Capture task, it was beneficial for subjects to constantly move forward (toward the target along the x-axis), regardless of drift type, to reduce total task time. When any condition required the subject to stop forward motion to take other actions, we expected to see an increase in total trial time. Here TL and NB were observed to have increased trial times, which supports hypothesis one. Increased time and reduced grapple success rates were observed for NB as well as

Table II. Means and SD of Input Time Data (Overall and By Experimental Order).

	FM (s) (N = 260)		NB (s) (N = 260)		RL (s) (N = 260)		TL (s) (N = 260)	
	MEAN	**SD**	**MEAN**	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
OVERALL								
Trial Time	34.39	8.14	46.29	15.45	33.83	7.63	74.33	16.18
Total Translation Time	31.67	7.11	35.47	9.67	30.80	5.93	62.61	12.75
Total Rotation Time	13.33	7.29	5.78	3.72	10.51	5.39	24.06	15.64
Multi-Translation Time	28.75	5.77	31.54	7.54	28.07	4.28	*	*
Multi-Rotation Time	3.11	4.04	2.13	2.33	*	*	6.80	8.57
Bimanual Time	13.17	6.92	*	*	10.36	5.26	20.57	13.37
FM-FIRST ORDER (FM, NB, RL, TL)								
Trial Time	37.27	10.56	50.09	19.46	32.50	5.10	73.75	16.92
Total Translation Time	33.96	9.34	37.85	12.25	30.47	4.50	61.62	12.78
Total Rotation Time	15.06	8.50	6.71	4.74	10.50	5.44	27.12	16.47
Multi-Translation Time	30.55	7.27	33.66	9.40	28.48	3.55	*	*
Multi-Rotation Time	3.96	5.02	2.70	2.82	*	*	8.46	9.09
Bimanual Time	14.76	7.92	*	*	10.40	5.41	22.70	13.52
TL-FIRST ORDER (TL, RL, NB, FM)								
Trial Time	31.50	2.18	42.49	8.43	35.16	9.34	74.91	15.44
Total Translation Time	29.37	1.89	33.09	5.12	31.14	7.08	63.61	12.69
Total Rotation Time	11.60	5.34	4.85	1.90	10.52	5.35	21.01	14.18
Multi-Translation Time	26.96	2.72	29.42	4.10	27.67	4.89	*	*
Multi-Rotation Time	2.26	2.47	1.57	1.52	*	*	5.15	7.70
Bimanual Time	11.58	5.32	*	*	10.32	5.13	18.43	12.92

* Where metrics are not applicable due to test condition, there is no data shown.

TL when compared to FM trials. However, with NB these measures were affected to a lesser extent than for TL. The different degradations of NB and TL on trial time and workload are indications that strategy was altered differently by TL than by NB, supporting hypothesis two.

There was no significant difference in trial success, trial time, or workload between FM and RL. When developing new control interface designs, hardware limitations may restrict the number of DOF for the input. This finding highlights that mapping rotation to a single command at a time is a viable option in interface design without loss in performance. With order taken into account, for FM and RL, the condition shown first had a higher workload than the other. This change in workload is the type of variation expected if the same condition were being tested twice at different times; with exposure, workload was reduced.

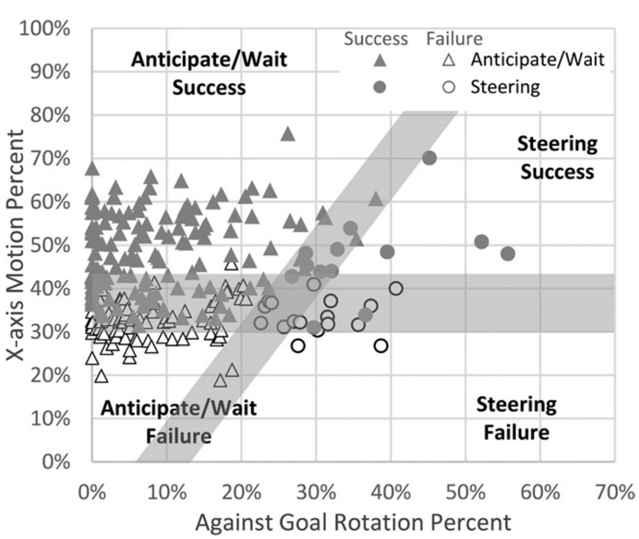

Fig. 6. TL trials categorized as translational-anticipate-and-wait (triangles) or end-effector steering strategy groups (circles). Successes are indicated by filled symbols and failures by open symbols. The gray regions represent separating lines between the four categories. The horizontal gray region highlights the overlap between successes and failures for x-axis motion percent. The sloped gray region indicates trials within 5% of the 18.412-s cut-off for against-goal rotation time.

A shift in multirotation technique associated with the two emergent strategies under translation limiting was observed. During the TL condition, subjects could not simultaneously maintain all three elements of normal tracking (visual tracking, closing distance, and alignment). To overcome the limitations of this condition, subjects followed two strategies, each maintaining two of the three tracking components. As described previously, the translational-anticipate-and-wait strategy focused on alignment and closing distance, while the end-effector steering strategy sacrificed initial alignment maintenance in favor of visualizing the grapple pin and closing distance. The higher success rate for translational-anticipate-and-wait trials suggests that this strategy is more advantageous, and should be promoted in training for similar target-reaching robotics tasks in which all components of tracking may not be used concurrently. The lower success rate for end-effector steering indicates that this strategy could be detrimental to overall performance under any condition, including FM. However, the total number of end-effector steering trials was small, and given the discrepancy in the size of N between the two strategies, further experimentation with strategy instruction would be required before any definitive recommendations to train against end-effector steering could be made. However, the steering strategy would also be detrimental from an operations perspective, as it would require more fuel, a limited resource.

Input technique of the same type as end-effector steering is commonly used for basic movement by players in role-playing video games with "look" or "pointing" control.[2] However, the subject group in this study did not have enough variation in video game exposure or large enough sample size to determine any correlation between gaming experience and use of the steering strategy. Among the nine subjects who did use end-effector steering during experimental trials, frequency of use varied. Only 1 subject used the steering strategy consistently throughout their trials, while 16 subjects alternated between both strategies using end-effector steering 3 to 5 times total, and 3 used end-effector steering only once before going back to translational-anticipate-and-wait. The one subject who favored end-effector steering was also the only person to attempt this strategy during the readiness test trials. This suggests that even though subjects were all reliably completing the task by the end of the readiness test and considered fully trained, there were still elements of learning and strategy development during the experimental trials.

Reduced rotation time during the NB condition indicated an effect on technique from the removal of bimanual control. In the NB condition, subjects had to pause forward motion to perform rotation, and while technique was altered, the standard tracking strategy was still present. Subjects were still able to maintain visual and close distance while adjusting translational alignment, with occasional rotational alignment adjustments. The effect was a minimization of rotational orientation adjustment, such that increased trial time as compared to FM was accompanied by shorter rotation and multirotation time. The reduction in rotation indicates more precise rotational inputs, limiting overshoot and excessive movement. This suggests that NB may have potential use in training to optimize rotational input efficiency, which depending on the system operated can save limited resources such as power or fuel.

These data supported that FM and RL performance were not significantly different. Yet, FM techniques still utilized occasional multirotation. Thus, we can infer that for this task, multirotation may not be necessary for performance, but it can be used effectively with training. However, a dual-joystick study by Wang[15] recommended that it is desirable to train novice users to avoid unnecessary multirotation, or "train out" unintentional rotation cross-coupling. Given the success of the RL condition in this study, and the efficient rotation seen during NB, it is possible that combinations of RL and NB restrictions on 6 DOF controllers could be useful in early training of novice users.

There were limitations in this study that may affect generalization of these results. As discussed above, subject spatial abilities were assessed and order group balanced using MRT scores. Most subjects in this study scored above average, thus it is not known how spatial reasoning skill would affect limited DOF performance. The Canadarm2 joystick interface used for this study was a bimanual system. It is unclear if the relationships between translation and rotation observed would apply to a unimanual interface. However, past studies in asymmetric bimanual rhythmic tasks suggest that even when motions between hands are different, the brain can perceive the actions of the hands as a single task, allowing coordination to persist.[5] This indicates that operation using the bimanual joystick configuration used for this study may have been perceived by the brain as a single task. Operations with a unimanual interface may be perceived similarly, suggesting that strategy observations from this study may translate to single-handed interface use, though further investigation with unimanual interfaces is required. Additionally, the simulator interface was rate controlled. Further study would need to be conducted to determine if the design and training recommendations made here would be useful in position-controlled systems. Although some position-controlled interfaces follow a master-slave paradigm,[13] which are based on human hand placement/orientation and less likely to involve interface DOF reductions, other experimental interfaces use position control primarily for the translation aspects of operation.[10] Such systems may benefit from incorporation of simultaneous rotations or rotation limiting. The current study evaluated the SSRMS joysticks as a case study in a 1-g environment. Follow-on studies could examine how the motor performance and decision-making are altered in a microgravity environment. Future investigations may also include study of DOF limitations across a range of common interfaces, such as the Wii-mote or other joystick-type controls used for robotic rovers or construction vehicles, to assess for the trends seen here across a broader set of design applications.

In conclusion, this research aimed to determine the effect of reducing control interface DOF on telerobotic operations. No significant difference in performance or workload was seen between full multiaxis and rotation limited controls. Preventing simultaneous rotation and translation minimized use of multirotation and rotation in general, instead favoring time spent translating. It is recommended that future interfaces use such separation in training to optimize rotation use and efficiency. Although translation limiting resulted in poorest performance and highest workload, strategies observed indicate that tactics of anticipation and alignment during goal-reaching tasks are more efficient than steering a robot and aligning later. These findings have potential to guide design and training requirements for future telerobotic interfaces.

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