Human Performance Time Model of Spacecraft Control Panel Operation in Simulated Microgravity

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BACKGROUND: Human performance modeling plays an important role in the design and management of human spaceflight missions. Previous studies reported that manual control task time increased in microgravity conditions. The current study aimed to find a modeling method that can quantify and predict the task time of spacecraft control panel operation in the simulated microgravity condition.

METHODS: We proposed the application of a predetermined elemental task method together with an information processing time model to quantify both physical motion time and cognitive time. The time increment due to microgravity was hypothesized to be proportional to physical motion time. The total task time in the microgravity condition could be calculated as the model time from the normal ground condition plus the predicted time increment. Human data were collected from an experiment asking participants to perform six emergency operating procedure tasks in both normal ground and simulated microgravity conditions.

RESULTS: The proposed method resulted in good fitness to human data in both conditions, as shown by both regression fitness (R^2 values = 0.99) and modeling error measures (root mean square error ≤ 3.3 s; mean absolute percentage error ≤ 16.1%).

CONCLUSIONS: Although the method has its limitations, the current findings suggest that it has value in aerospace human factors and ergonomics applications.

KEYWORDS: harness suspension, spaceflight human performance, predetermined elemental task method, MODAPTS.

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Human performance modeling (HPM) plays an important role in the design and management of human spaceflight missions. Because of the expense and complexity of performing human research in space, it is valuable to estimate astronauts' performance using methods that can be conducted on the ground.[12] Modeling methods provide opportunities to identify human performance issues and prepare countermeasures in advance. In this paper, we present a new way of analyzing how spacecraft control panel operation time performance is affected by simulated microgravity, which is an initial step to analyzing the effect of microgravity in space.

During a spaceflight, it is often very difficult for astronauts to maintain performance as good as their training performance on the ground due to the extreme conditions in space.[13] Many studies have examined and discussed the challenges, including psychosocial,[18] physiological,[3] and cognitive issues.[20] In particular, control panel interaction, one of astronauts' most frequently performed tasks, is affected. Previous studies have reported that manual control task time increased in space.[22] A concern is whether astronauts would still be able to complete emergency operating procedures quickly enough.

Operational procedures involve both physical and cognitive activities. Previous studies suggested that manual control task time increase in microgravity is mainly due to changes in physical performance rather than cognitive performance. For example, researchers found that manual control movement time increased,[5] fine motor tracking performance degraded,[25] and eye gaze control was also affected in microgravity.[1] This decrease

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of manual control performance has been attributed to the alterations of proprioception and motor control processes caused by microgravity. Exposure to microgravity may produce sensorimotor discordance because adult sensorimotor systems that have adapted to Earth gravity become miscalibrated to the microgravity environment.[6] However, little change of cognitive performance has been associated with microgravity (note that here microgravity only refers to reduced gravity, not the space mission environment in general; the space mission environment often also involves other factors such as loss of sleep and fatigue). For example, short term memory and decision making performance were reportedly not affected by microgravity.[15] Although crewmembers of long-duration space missions showed impaired cognitive functions, it was mostly due to extended duration of work shifts and fatigue rather than microgravity.[4]

In summary, previous studies showed that 1) microgravity reduced motor performance and increased physical motion time (PMT), which refers to the time duration of body movement in a task, such as moving hands and pressing buttons; 2) microgravity (just microgravity, not considering fatigue or sleep loss) did not affect short term memory and decision making performance, meaning no time change on cognitive time (CT), which refers to the time duration of cognitive activities in a task; 3) extended work shifts and fatigue impaired cognitive function (that means increased CT). Since the focus of the current study is on the effect of microgravity alone, based on the previous findings 1 and 2, we hypothesized that the increased time increment caused by microgravity should be proportional to PMT rather than CT. As a result, it is necessary to model and separate PMT and CT.

In the field of HPM, previous research has developed many methods that can be used to analyze operators' performance.[8] In particular, predetermined elemental task methods are specifically suited for PMT modeling. Such methods decompose a task into elemental components and then look up the time from predetermined tables, which are based on existing theories and empirical results. There are many methods such as Modular Arrangement of Predetermined Time Standards (MODAPTS),[24] Methods-Time Measurement (MTM),[23] and a recent model developed for in-vehicle speech interfaces.[21] Among them, MODAPTS has been favored by many researchers and engineers due to being convenient to apply and its good fitness to human data.[27,28] For example, previous studies have used it to model manually assembling consumer electronics tasks,[14] manual warping tasks in fabric manufacturing,[19] and soldier equipment assembling tasks.[2]

A major limitation of MODAPTS, however, is in modeling cognitive activities. Its task elements are mostly about physical movement. The only cognitive element (code name D for Decide) represents simple confirmation time, which refers to the time duration of confirming that the target information is seen or heard following task procedures. It corresponds to code D in MODAPTS. Therefore, MODAPTS alone cannot account for all CT. Additional models should be used to account for information processing time (IPT), which refers to the time duration of interpreting the meaning of information on the display or determining what information should be entered on the control panel. For example, Hoffmann et al.[17] modeled mail sorting time performance using MODAPTS together with an IPT model. It assumed that IPT (e.g., interpreting zip codes and addresses on the envelope) is proportional to the number of information items examined. The time ratio (i.e., the amount of time per information item) can be determined by fitting human data. Their combined model was able to produce time performance similar to the human results. In the current study, we adopted the same strategy: PMT was modeled using MODAPTS, and IPT was modeled in a similar way that assumes IPT is proportional to the number of information items.

Due to the difficulty of running tests in space, many studies in this field often use simulated microgravity methods. The current study used harness suspension, which is one of the most frequently used methods.[11] Typically, the suspension technique uses multiple pieces of harness to hang the operator in the air. Each harness is placed at around the mass center of each body part to support the weight and simulate reduced gravity. Compared with other techniques such as parabolic flight and neutral buoyancy immersion, harness suspension is easier to implement, costs much less, and can simulate reduced gravity for a long period of time. In contrast, parabolic flight can only produce short periods of weightlessness, usually less than 60 s.[26] Buoyancy immersion requires submerging operators in a water tank, which makes it not suitable for testing control panel operation tasks due to the difficulty of interacting with computer panels under water.[7] Using harness suspension, previous studies have investigated the effects of simulated microgravity on muscle, bone, blood, and immune systems. In addition, it has also been used to study the changes of human walking mobility and metabolic cost in simulated microgravity.[16] However, it is important to note that the psychomotor mechanisms underlying the effects of harness suspension may be different from the mechanisms underlying the effects of real microgravity in space, even if the magnitudes of effects could be similar. In the current study, we compared the time performance of spacecraft control panel operation tasks between suspension and nonsuspension (normal ground) conditions in order to collect human data for the modeling work.

Previous studies suggested that the harness suspension method presents both value and challenges. It is still an open question regarding whether it is a suitable method to study the effect of microgravity on human performance time. We believe this question can be addressed in three steps. First, we should test if harness suspension can significantly increase performance time. This is relatively easy to test on the ground. If this first step has a positive answer, then the second step is to test if the magnitude of time increment in the suspension condition is similar to the magnitude of increase in space. This test requires astronauts testing in space. If the second step also has a positive answer, then harness suspension could be a good engineering method. Finally, the third step is to examine if the mechanism causing time increment in suspension is the same as the mechanism causing time increment in space. This last step is more theoretical and related to how human motion adapts to the change of environment. Even if the mechanisms are not identical, it may still be a useful engineering tool, as long as the prediction on time increment is accurate enough. In this study, we started from the first step. If the results are promising, we will then plan for the second step.

The type of operation examined in this study was an emergency operation. Emergency operating procedures (EOPs) are plans of action in response to emergent events. Astronauts usually receive extensive training in EOPs. We chose EOP tasks because time performance is critical in EOPs. Simulating and estimating EOP task time in microgravity can support the evaluations of both EOP design and system reliability. In addition, EOPs have explicit and standardized procedures, which provide the convenience of experimental control. It is important to note that the EOPs tested in this study are all standardized procedures. If any emergency that is not described by any standard EOP happens, astronauts and ground control have to improvise. Such truly unexpected scenarios require more complex cognitive processing and are not the focus of this study. In that case, models from the cognitive architecture literature could be considered.[8]

METHODS

Subjects

Participating in this study were 24 male adults recruited around the campus of a Chinese university. They had an average age of 23 yr (SD = 2 yr). The gender factor was not included in the current study as a variable. The all-male participant pool was similar to the fact that the majority (over 90%) of the current Chinese astronauts are men. All participants were right-handed, in normal physical condition, and had normal or correct-to-normal vision. The study protocol was approved by the ethics committee from the Astronaut Center of China prior to volunteer recruitment. Each subject provided written informed consent before participating.

Equipment and Materials

The EOP tasks used in the current study were adapted from EOPs used by Chinese astronauts. The original procedures, designed by the China Astronaut Research and Training Center, specify the standard protocols to diagnose and recover from system malfunctions. The EOP tasks in the current study were simplified versions, with the decision making branches reduced to a serial procedure; that is, each tested EOP task had only one cause of malfunction so that different trials with the same EOP task could result in the same manual control steps. This design reduced the need for complex cognitive processing. The major reason to do so is to retain some cognitive elements for the examination of our assumption while making the cognitive elements simple enough so that they can be analyzed by our model. In addition, the EOP simplification also allowed participants to sufficiently learn and practice the tasks within the duration of this study.

The control panel used in the current study was same as the one used in Chinese astronaut training and Shenzhou spacecrafts. As shown in **Fig. 1**, there are two major monitors (Areas A and B) and two major control units (Areas R and L) on the control panel.

A total of six EOP tasks were examined in this study, including monitor malfunction (EOP 1), electrical power malfunction (EOP 2), thermal control system malfunction (EOP 3), guidance, navigation, and control system malfunction (EOP 4), propulsion system malfunction (EOP 5), and oxygen pressure control system malfunction (EOP 6). The tasks were selected to cover a range of different complexity levels. EOP 1 and 2 are low complexity; EOP 3 and 4 are medium complexity; EOP 5 and 6 are high complexity. The complexity level of each task was evaluated using the entropy method of spaceflight operation complexity.[29] **Fig. 2** shows the number of information items and the number of operation steps in each task. Operators need to visually attend specific areas on the control panel, interpret key information (e.g., oxygen tank pressure and temperature), and press buttons and switches to issue control commands. Here an information item refers to a value that needs to be read from the display or entered on the control panel. A value could be a numerical value (e.g., 12°C), a state value (e.g., switch position ON), or a passcode. For example in EOP 3, when reading the temperature from the display, the temperature value counts as one information item. When setting a thermal control valve to the ON position, the ON state value counts as one information item. EOP 3 has two steps that require reading temperature and two steps that require setting control valve states. Therefore, the total information item in EOP 3 is four.

The harness suspension system used in the current study is illustrated in **Fig. 3**. The system provided nine points of weight support, located at the forearms, torso, upper legs, lower legs, and feet. Participants were suspended horizontally (chest facing ground). The interface was placed vertically. The distance between the interface and each participant was adjusted individually to allow comfortable control.

Procedure

The participants first gave their written consent and then practiced all six EOP tasks. Each task was practiced at least 20 times in the normal condition without suspension, until the participants could complete the tasks fluently without any error. After practice, the participants completed the six EOP tasks in the normal ground condition. The order of the six tasks was

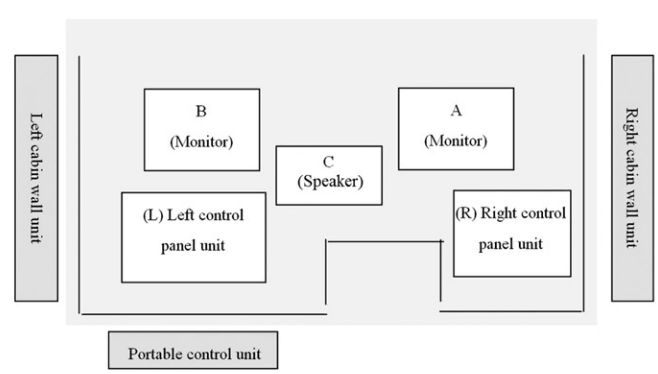

Fig. 1. Illustration of the control panel used in the current study.

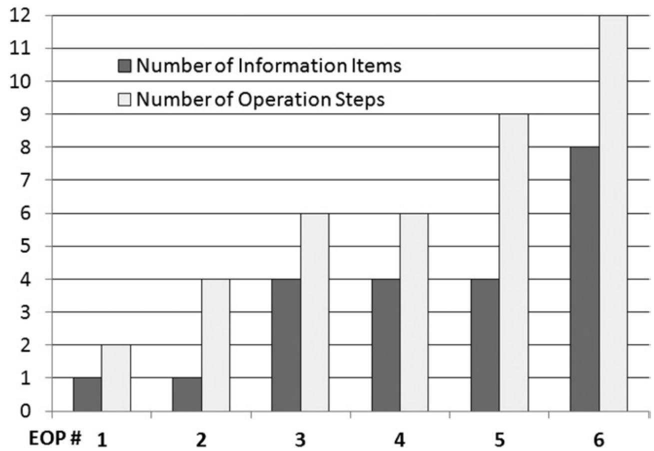

Fig. 2. The number of information items and the number of operation steps in each EOP task used in this study.

randomized. They then took a short break and completed the six tasks again in the suspension condition. This procedure ensured that the participants were well-practiced on the ground and then tested in the reduced-gravity condition, just as astronauts experience in their training and spaceflight missions. We did not counterbalance the order of the two conditions. The reason is that the suspension task could cause stronger fatigue and discomfort. If it was tested first, a much longer break would be needed before running the following normal ground condition. In contrast, when the normal ground condition was tested first, its impact on the following suspension task would be minimal.

Regarding the modeling procedure, MODAPTS is a predetermined elemental task method for describing work sequences and the time needed to complete the work.[24] A work sequence in MODAPTS is divided into task elements. Each element is denoted by a code—a letter followed by an integer. The letter represents the type of activity, and the integer represents the time required to perform the task element in the unit of MOD. One MOD is 0.129 s. MODAPTS categorizes the task elements as different kinds of activities such as Move (M), Get (G), Put (P), Decide (D), Eye Control (E), and Extra Force (X). Depending on the condition, each kind of activity may have different cases that result in different numbers of MOD. For example, Move activities have MODs ranging from 1 to 7, depending on the body parts that are involved in the movement. Get and Put elements are related to grasping and releasing objects from the hand. They are not used in the current model because the EOP tasks did not involve moving objects. The codes and meanings of activities used in the current study are listed as follows. M2 (two MODs) is the movement of the fingers and the hand around 5 cm. M3 (three MODs) is the movement of the hand and the forearm around 15 cm. M4 (four MODs) is the movement of the hand and the whole arm around 30 cm. X4 (four MODs) is applying extra pressure to overcome resistance in an activity. E2 (two MODs) represents eye travel and fixation. D3 (three MODs) represents simple confirmation time. Extra Force (X) was used to describe button pressing and key switching motion because the buttons and switches on the spacecraft are designed to require extra force in order to prevent accidental activation. Note that Decide (D) is the only cognitive element in MODAPTS, whereas the others are physical motion elements. The D element only provides a very rudimentary description of simple mental confirmation activities, such as confirming target location. For a complete set of MODAPTS activities, we refer the readers to the related literature.[24]

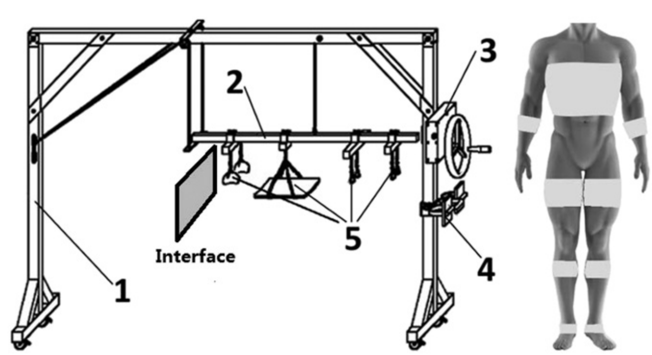

Fig. 3. Illustration of the harness suspension system (left) and the areas of harness support on the human body (right), not proportional in size (Number 1, supporting frame; 2, suspension beam; 3, height adjustment; 4, foot restraint; 5, harness).

In the MODAPTS analysis of the six EOP tasks (normal ground condition), the following principles were used. Each EOP was decomposed into multiple steps based on the EOP descriptions and observations from the participants doing the tasks. There were in general three kinds of steps—confirming the task, moving upper extremities, and viewing system readings. Task confirmation happened at the very beginning of each EOP. When the participants need to mentally confirm the EOP scenario (indicated by alarm cues provided to the participants), code D3 (the only cognitive element in MODAPTS) was used to represent this step. Upper extremity movements refer to moving the whole arm, forearm, or fingers to activate controls. Each movement typically consists of a group of three elements, an M code (M2, M3, or M4 depending on the body part that moves), an E2 code (eye fixation looking at the target destination), and an X4 code (apply extra force to activate the control). Viewing system readings refers to eye movement and related mental confirmation of the target information (e.g., oxygen tank pressure and temperature). A group of two codes, E2 and D3, were used for each viewing.

An IPT model was developed to account for the cognitive activities beyond the simple confirmation that can be covered by MODAPTS' code D. Combining both models, the total task time can be decomposed into MODAPTS' M, X, E, and D plus this IPT. The PMT is the sum of M, X, and E time. CT is the sum of D and IPT. Following similar ideas as used in previous research,[17] the IPT model assumed that IPT is proportional to the number of information items in the tasks. Although different information items may require different processing time, in the current version, we assumed that all items require the same processing time on average. Future studies can further examine more detailed models.

After the human total task time (normal ground condition) was obtained and the PMT was analyzed from MODAPTS, human IPT was computed by subtracting M, X, E, and D times from the total task time. Then regression was used to determine the ratio between information item number and IPT. The human time increment increase due to suspension was calculated by subtracting the total task time in the normal ground condition from the total task time in the suspension condition. Then we compared two hypotheses. H1 is the original hypothesis that time increment is proportional to PMT, following expectation from our literature review. H2 is the alternative hypothesis that time increment is proportional to CT. Finally, the model's predicted total task time in the suspension condition equals to the sum of model PMT, model CT, and model time increment.

RESULTS

Behavioral results obtained from both normal and suspension conditions contained no erroneous actions, because no such actions were recorded. Among the results collected from the 24 participants, one data point from the suspension condition of EOP 6 was identified as an outlier with a value deviated more than 3 SDs from the mean value, so it was removed. The resulting averaged times were computed and shown in **Table I**. Repeated measures ANOVA was performed using SPSS (version 21) to examine the effects of task type (EOP 1–6) and task condition (normal ground vs. suspension) on total task time.

Statistical Analysis

Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of task type [$\chi^2(14) = 53.47$, $P < 0.001$] and the interaction between task type and task condition [$\chi^2(14) = 32.57$, $P = 0.004$]. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\epsilon = 0.503$ and 0.646 for the two effects, respectively). All effects on task time were significant. There was a significant main effect of task type [$F(2.5, 55.3) = 586.60$, $P < 0.001$, $\eta^2 = 0.941$]. Pairwise comparison showed that all the task type pairs were significantly different (P-values < 0.05, Sidak correction) except for the pair between EOP 3 and EOP 4 ($P = 1.000$). In general, more complex tasks required longer time to complete. There was a significant main effect of task condition [$F(1, 22) = 20.82$, $P < 0.001$, $\eta^2 = 0.004$]. Task time was significantly longer in the suspension condition. The time increments are listed in Table I. In addition, the interaction effect was also significant [$F(3.2, 71.1) = 2.79$, $P = 0.043$, $\eta^2 = 0.002$], which means that the time increment was even longer in more complex EOP tasks.

MODAPTS task analysis and modeling were applied to all six EOPs in the normal ground condition. The time results are shown in **Table II**. The details of the elemental task decomposition for each EOP are listed in **Table III**. When evaluating the model fitness, two aspects should be considered. The first is the capability to capture the difference between the six EOP task conditions. The model's time should be longer when the task complexity is greater, as observed from the human results. Regression can be used to test this aspect. The regression of human normal ground task time on total MODAPTS model time was significant [$F(1, 5) = 1815.0$, $P < 0.001$; $R^2 = 1.00$; intercept was expected to be zero]. This result means that the MODAPTS method alone can capture the difference (time increasing trend) among the six EOP tasks. The second aspect is regarding modeling error or deviation, which refers to the difference between model values and corresponding human values. This aspect is often measured by root mean square error (RMSE) and mean absolute percentage error (MAPE).

When measuring the difference between model values ($x_{\text{model, i}}$) and corresponding human values ($x_{\text{human, i}}$), the formula of RMSE is:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{\text{model, i}} - x_{\text{human, i}})^2}{n}}, \qquad \text{Eq. 1}$$

where n is the sample size. The formula of MAPE is:

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{x_{\text{model,i}} - x_{\text{human,i}}}{x_{\text{human,i}}}\right|\%. \qquad \text{Eq. 2}$$

For example, the values from the MODAPTS only method were 2.2, 6.9, 12.2, 14.2, 25.0, and 51.4 s for the six EOP conditions. The corresponding human values were 7.2, 11.5, 19.7, 20.4, 39.0, and 76.0 s ($N = 6$). Following the above two equations, the results were RMSE = 12.5 s and MAPE = 41.0%.

The MODAPTS method alone has a large error. Our explanation of this poor fit is that the MODAPTS elements do not account for IPT. Assuming the MODAPTS only time (i.e., M+X+E+D element time) was analyzed accurately for the six EOP tasks, the human IPT (IPT_{human}), which refers to IPT obtained from human data, can be computed by subtracting the MODAPTS-only time values from the total human ground

Table I. Average Task Completion Time Human Results from Emergency Operating Procedure (EOP) Tasks in Different Conditions.

EOP #	TASK NAME	AVERAGE TIME (s) (SD)			INFORMATION PROCESSING TIME (IPT_{human}) (s)
		NORMAL GROUND	SUSPENSION	TIME INCREMENT	
1	Monitor malfunction	7.2 (3.5)	7.4 (3.2)	0.2	5.0
2	Electrical power malfunction	11.5 (2.3)	14.0 (2.9)	2.5	4.6
3	Thermal control system malfunction	19.7 (5.2)	22.2 (6.0)	2.5	7.5
4	Guidance, navigation, and control system malfunction	20.4 (4.9)	23.1 (5.5)	2.7	6.2
5	Propulsion system malfunction	39.0 (8.3)	44.9 (9.3)	5.9	14.0
6	Environmental control system malfunction*	76.0 (11.1)	81.8 (12.7)	5.8	24.6

* In this task, participants waited for a total of 24 s when the machine was doing its work. This 24-s duration is included in the total task time.

Table II. Summarized Modeling Results.

	MODAPTS			IPT		MODAPTS + IPT (Hypothesis 1)		
EOP #	PHYSICAL MOTION TIME M+X+E (s)	DECIDE (D) ELEMENT TIME (s)	TOTAL TASK TIME MODAPTS PREDICTION (s)	IPT_{model} (s)	COGNITIVE TIME (D+IPT) (s)	TOTAL TASK TIME − NORMAL GROUND (s)	TIME INCREMENT (s)	TOTAL TASK TIME − SUSPENSION (s)
1	1.4	0.8	2.2	2.8	3.6	5.0	0.3	5.3
2	6.1	0.8	6.9	2.8	3.6	9.7	1.5	11.2
3	10.3	1.9	12.2	11.2	13.1	23.4	2.5	25.9
4	12.3	1.9	14.2	11.2	13.1	25.4	3.0	28.4
5	23.1	1.9	25	11.2	13.1	36.2	5.5	41.7
6	25.5	1.9	51.4*	22.4	24.3	73.8*	6.1	79.9*

Total task time (normal ground) = physical motion time (M+X+E) + Decide (D) + Information processing time (IPT); Cognitive time = Decide (D) + information processing time (IPT); Total task time (suspension) = total task time (normal ground) + time increment.
* In this task, participants waited for a total of 24 s when the machine was doing its work. This 24-s duration is included in the total task time.

condition time values. The resulting IPT_{human} values are listed in Table I. On the other hand, IPT_{model}, which refers to IPT predicted by the model, is proportional to the number of information items (N), so:

$$IPT_{model} = r\,N, \qquad \text{Eq. 3}$$

where r is a ratio parameter. Regression was used to find this ratio. The result showed a significant linear relationship [$F(1, 5) = 74.3$, $P < 0.001$; $R^2 = 0.94$]. The intercept was set at zero, because when there is no information item, time should be zero. The regression coefficient was 2.8 [$t(4) = 8.6$, $P < 0.001$). Therefore, 2.8 was used as the r value in Eq. 3. Using this equation, IPT_{model} values were calculated and listed in Table II.

The combined total task time in the normal ground condition predicted by the model ($T_{n,\,model}$) could be calculated as:

$$T_{n,\,model} = (M + X + E + D) + IPT_{model}. \qquad \text{Eq. 4}$$

The results are plotted in **Fig. 4A** (MODAPTS+IPT). In comparison to the model fit of MODAPTS only, the results from the combined model also have a significant linear relationship to the human results [$F(1, 5) = 700.9$, $P < 0.001$; $R^2 = 0.99$; intercept was expected to be zero], but the combined model has a much smaller modeling error (RMSE was 3.1 s and MAPE was 16.6%). Again, this shows that both regression and modeling error measures should be considered when evaluating model fit.

Next, to model the time increment, our expectation was that PMT (MODAPTS' M+X+E) in the normal ground condition should be a better predictor than CT (MODAPTS' D+IPT). When analyzing the results from each EOP, we noticed some specific cases in favor of this expectation. As can be seen from Table I and Table II, when comparing EOP 4 and 5, their CTs (D+IPT) were the same, the PMT (M+X+E) from EOP 5 was about twice as large as the value from EOP 4; and the human time increment from EOP 5 was also about twice as large as the one from EOP 4 (proportional to PMT). A similar pattern can also be found when comparing EOP 1 and 2. On the other hand, when comparing EOP 5 and 6, the CT from EOP 6 was almost doubled in comparison to EOP 5, but the PMT was similar, and the human time increment was also similar.

Formally, Eqs. 5 and 6 below were used to compute the model time under suspension for two alternative hypotheses. Hypothesis 1 (H1) assumes that time increment due to suspension is proportional to PMT. Therefore, the total task time under suspension predicted using model H1 is:

$$T_{s,\,model,\,H1} = T_{n,\,model} + k(M + X + E), \qquad \text{Eq. 5}$$

where k is a ratio parameter. Hypothesis 2 (H2) assumes that time increment is proportional to CT. Therefore, the total task time under suspension predicted using model H2 is:

$$T_{s,\,model,\,H2} = T_{n,\,model} + j(D + IPT_{model}), \qquad \text{Eq. 6}$$

where j is a ratio parameter. Linear regression was used to estimate the values of k and j, in a way similar to estimating ratio r in Eq. 3. Both regressions were significant. The first regression had $R^2 = 0.98$ [$F(1, 5) = 315.4$, $P < 0.001$; intercept was expected to be zero]. The value of k was estimated at 0.24 [$t(4) = 17.8$, $P < 0.001$]. The second regression had $R^2 = 0.88$ [$F(1, 5) = 35.9$, $P = 0.004$; intercept was expected to be zero]. The value of j was estimated at 0.26 [$t(4) = 6.0$, $P = 0.002$].

When evaluating model fitness to human suspension task time, model total task times were calculated using Eqs. 5 and 6; both regression and modeling error measures were considered. Regarding H1, the regression of human suspension task time on the model result ($T_{s,\,model,\,H1}$) was significant [$F(1, 5) = 749.2$, $P < 0.001$; $R^2 = 0.99$; intercept was expected to be zero]; RMSE was 3.3 s, and MAPE was 16.1%. Regarding H2, the regression of human suspension task time on the model result ($T_{s,\,model,\,H2}$) was also significant [$F(1, 5) = 509.5$, $P < 0.001$; $R^2 = 0.99$; intercept was expected to be zero]; RMSE was 4.0 s, and MAPE was 17.2%. The results are plotted in **Fig. 4B**. Overall, both alternatives fit well to the human data; however, H1 is slightly better in terms of smaller RMSE and MAPE. Considering suggestions from the literature as we reviewed in the introduction, our conclusion is still in favor of adopting H1 in the model.

Combining Eqs. 3 and 4, the model task time in the normal ground condition is:

$$T_{n,\,model} = (M + X + E + D) + r\,N. \qquad \text{Eq. 7}$$

Plugging Eq. 7 into Eq. 5, the model task time under suspension is:

$$T_{s,\,model,\,H1} = (M + X + E + D) + r\,N + k(M + X + E). \qquad \text{Eq. 8}$$

Table III. MODAPTS Modeling Results for the EOP Tasks in the Normal Ground Condition.

				SUM OF MOD			
TASK	**STEP**	**CODE**	**MOD (TIME: s)**	**M**	**X**	**E**	**D**
1. Monitor malfunction	Task confirmation	D3	3				
	Select comprehensive display page	M3E2X4	9				
	View orbit control	E2D3	5	**M**	**X**	**E**	**D**
		Total MOD (s)	17 (2.193 s)	3	4	4	6
2. Electrical power malfunction	Task confirmation	D3	3				
	Select power system page	M3E2X4	9				
	View charging state	E2D3	5				
	Set charging switch	(M3E2X4) × 3	27				
	Confirm the set	M3E2X4	9	**M**	**X**	**E**	**D**
		Total MOD (s)	53 (6.837 s)	15	20	12	6
3. Thermal control system malfunction	Task confirmation	D3	3				
	Select thermal control page 1	M3E2X4	9				
	View temperature of detector 1	(E2D3) × 2	10				
	Set thermal control valve 1	(M3E2X4) × 3	27				
	Select thermal control page 2	M3E2X4	9				
	View temperature of detector 2	(E2D3) × 2	10				
	Set thermal control valve 2	(M3E2X4) × 3	27	**M**	**X**	**E**	**D**
		Total MOD (s)	95 (12.255 s)	24	32	24	15
4. Guidance, navigation, and control system malfunction	Task confirmation	D3	3				
	Input six numbers in right panel	M4 + (M2X4E2) × 6	52				
	Operate a push-and-pull switch of right panel	M2E2X4	8				
	Operate two buttons of right panel	(M3E2X4) × 2	18				
	View sign light	E2D3	5				
	Operate reset switch	M3E2X4	9				
	View information page	(E2D3) × 3	15	**M**	**X**	**E**	**D**
		Total MOD (s)	110 (14.19 s)	27	40	28	15
5, Propulsion system malfunction	Task confirmation	D3	3				
	Operate composite key 1 of left panel	M4 + (M3E2X4) × 4	40				
	Select propulsion system page	(M4E2X4) × 2	20				
	View power condition 1	E2D3	5				
	Operate composite key 2 of left panel	M4 + (M3E2X4) × 4	40				
	View power condition 2	E2D3	5				
	Operate composite key 3 of left panel	M4 + (M3E2X4) × 4	40				
	View connection condition 1	E2D3	5				
	Operate three keys of left panel	M4 + (M3E2X4) × 3	31				
	View connection condition 2	E2D3	5	**M**	**X**	**E**	**D**
		Total MOD (s)	194 (25.026 s)	69	68	42	15
6, Environmental control system malfunction	Task confirmation	D3	3				
	Enter environment control system page	M4E2X4	10				
	View the flow of air supply	(E2D3) × 2	10				
	Operate row key and column key 1 of left panel	(M3E2X4) × 2	18				
	System waiting time	(machine time)	46.5 (6 s)				
	Operate row key, column key 1 and enter key of left panel	(M3E2X4) × 3	27				
	View oxygen partial pressure	E2D3	5				
	Operate row key and column key 2 of left panel	(M3E2X4) × 2	18				
	System waiting time	(machine time)	46.5 (6 s)				
	Operate row key, column key 2 and enter key of left panel	(M3E2X4) × 3	27				
	Operate row key and column key 3 of left panel	(M3E2X4) × 2	18				
	System waiting time	(machine time)	46.5 (6 s)				
	Operate row key, column key 3 and enter key of left panel	(M3E2X4) × 3	27				
	View total pressure	E2D3	5				
	Operate row key and column key 4 of left panel	(M3E2X4) × 2	18				
	System waiting time	(machine time)	46.5 (6 s)				
	Operate row key, column key 4 and enter key of left panel	(M3E2X4) × 3	27	**M**	**X**	**E**	**D**
		Total MOD (s)	399 (51.471 s)	64	84	50	15

Note: One composite key included four buttons; 1 MOD = 0.129 s.

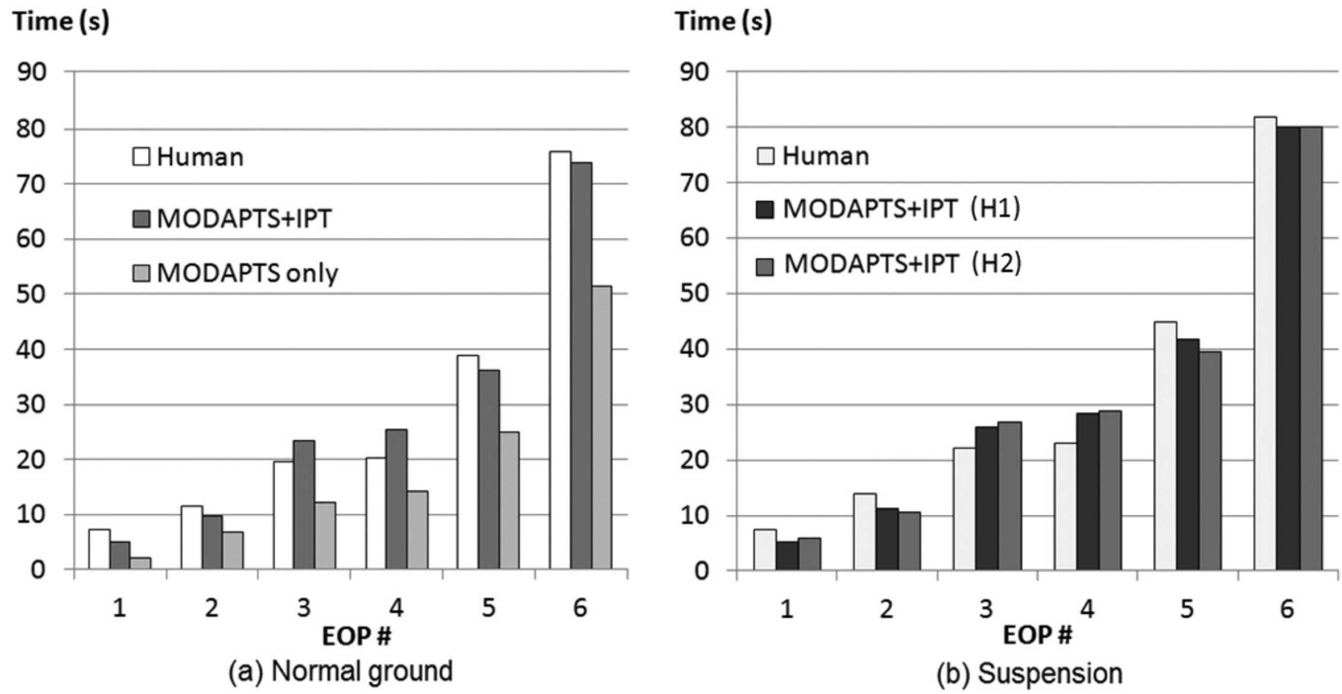

Fig. 4. Human and model total task time results in both A) normal ground and B) suspension conditions.

Using the two equations with parameter values r = 2.8 and k = 0.24, the final modeling results in this study were calculated and listed in Table II.

DISCUSSION

The current study aimed to find a modeling method that can quantify and predict the time performance of spacecraft control panel operation in simulated microgravity, which is the initial step before studying it in space. Such methods are extremely valuable for the design of spacecraft control panel interface and the management of human spaceflight missions, because system engineers must consider the effects of microgravity. Since previous studies found that the time increment is mainly related to PMT rather than CT, we proposed the use of a predetermined elemental task method (MODAPTS) to quantify the total PMT and hypothesized that the time increment could be estimated as proportional to PMT.

In addition to MODAPTS, an IPT model was used to account for information processing that cannot be modeled by MODAPTS. We assumed that IPT is proportional to the total number of information items in a task. The results showed a good fit by using a ratio of 2.8 s per item. This value seems to work fine in the scope of the current study with six relatively simple EOPs. In future work, more complicated models could be developed to account for the difference between different types of information items.

The combined model (MODAPTS+IPT) was tested with the human data collected from a simulated microgravity study. Moreover, the original hypothesis H1 was compared with an alternative H2. The results showed that in general both hypotheses could fit the human data, but H1 was slightly better. This result is in line with our initial expectation that time increment due to suspension is proportional to PMT.

Overall, the findings confirmed that the proposed modeling method has its value. While recent HPM studies have focused more on cognitive models,[9] the current study demonstrated that traditional PMT models such as MODAPTS can still have their application values. Future studies may also combine more sophisticated cognitive models with MODAPTS to more accurately predict CT.

There are still a few limitations in the current study. First, the durations of the tested EOP tasks were relatively short (within 1.5 min). Although it is enough to demonstrate the limitation of MODAPTS and the value of adding the IPT model, it seems not enough to produce strong contrast between the two alternative hypotheses about time increments. Future study could further examine this using tasks that take a longer time to complete. Adding a variety of tasks with different proportions of physical and cognitive elements could also help.

Second, the current model, as well as many human performance models in general, focuses on estimating mean performance rather than variance. It is a good starting point for building quantitative models, but the variation or range of performance is also important. Errors and accidents tend to happen when performance is at the lowest level. A random error term may be added to the current model to represent variation, but future modeling work needs to consider more about the mechanisms of performance variation. The current method covers EOPs, but is expected to have difficulty in analyzing truly unexpected scenarios where complex cognitive processing is required. Instead of MODAPTS and the current IPT model, cognitive modeling methods[8] are needed to analyze such cases.

Another limitation is the use of simulated microgravity. Although harness suspension is one of the most frequently used methods, it is still different from the microgravity environment in space. Future studies are needed to examine harness suspension in other types of human-computer interaction tasks and collect data from experiments conducted in space. In addition, the current study did not include gender as a factor in the experimental design. For human-machine interaction tasks (such as driving) that do not require a significant amount of physical effort, gender effects have been found in previous studies to be not significant or relatively small in terms of effect size.[10] Nevertheless, future studies can add gender as a factor in the experimental design to examine its effects.

Despite its limitations, the current study explores the feasibility of applying HPM to explaining and predicting the effects of microgravity on human performance. As an initial attempt to test the method, we started with a relatively easy-to-set-up design, using a college student population to test the two conditions with and without suspension. In an ideal experiment, real astronauts should be recruited and tested in three conditions—normal ground, ground suspension, and in space. The effects of microgravity should also be observed over a period of time to examine the level of gradual adaptation. Nevertheless, the results from the current study showed that task time in the suspension condition is longer than that in the normal ground condition, and therefore suspension may be used as a way to reproduce and represent astronauts' lack of adaptation in space for EOP task performance. Since the current study's results are promising, we are planning the next phases involving real astronauts and space testing in future space missions.

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