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Influence of Dry Immersion on the Characteristics of Cyclic Precise Hand Movements

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Abstract—The characteristics of precise hand movements in Dry Immersion (DI) have been studied. Motor tasks were cyclic single-joint hand movements corresponding to the length and orientation of the presented horizontal or vertical segment and carried out for 5 s with or without visual feedback. The studies were carried out with the participation of 35 test healthy volunteers divided into three groups: control ($n = 10$), 6-hour DI ($n = 11$), and 5-day DI ($n = 14$). In the control group, the test was carried out three times, lying on the couch, imitating the cyclogram of a 6-hour DI—once before DI, in the morning on the day of DI, and in the evening 2 h after the end of exposure. In the 5-day DI, tests were performed once before the start of the DI, on the 1st, 3rd, and 5th days of the DI, and also once after its completion. It is shown that the accuracy of movements in the control group does not depend on the measurement number, while in the experimental groups on the first day of DI there is an increase in the overestimation of the length of horizontal segments and an increase in the error in estimating the direction of vertical segments. The data indicate that DI affects the hand movement control system and can be considered as a suitable Earth model for studying fine movement disorders observed in microgravity.

Keywords: hand movements, Dry Immersion, gravity

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INTRODUCTION

In a space flight (SF), the working conditions of an astronaut are significantly different from those on the ground due to the state of weightlessness [1]. Weightlessness disrupts the activity of primarily the vestibular and support systems [2], which leads to the reorganization of the motor control system due to its reorientation to less gravitationally dependent systems, such as the visual one. Such a reorientation is accompanied by various orientation illusions [3] and leads to a slowdown in movements or loss of their accuracy [4, 5].

The study of the basic mechanisms of intersensory interactions and their disturbances is carried out in a complex way, both during the SF and in ground-based studies, which allow the use of both a larger sample size and a more rigorous cyclogram of studies. Along with models of parabolic flight [6], unloading of one of the limbs [7], underwater diving [8], and antiorthostatic hypokinesia [9], a model of gravitational unloading such as Dry Immersion (DI) is widely used in gravitational physiology [10, 11]. Most of the studies are devoted to the study of the influence of DI on the postural-tonic system [12]; the role of support afferentation in the system of hand movement control remains little studied. DI, unlike true microgravity, indirectly affects both the muscular apparatus of the upper limbs and their control system [13]; therefore, of interest is both the possibility of initiating hand movement disorders and the degree and dynamics of their severity, depending on the duration of the immersion impact. Note that DI may influence the internal representation of such motion planning components as amplitude and direction to a varying degree [14]. The purpose of this study was to analyze the effect of support unloading on the characteristics of precise hand movements during DI of various duration.

MATERIALS AND METHODS

The study involved three groups of healthy male volunteers. The control group included 10 people, aged 29.9 ± 5.4 years. The other two groups of subjects were under DI conditions, i.e., were immersed in a special bath filled with water covered with a waterproof film separating the body from the water [11]. The group of subjects who were in a 6-h immersion (DI-6h) included 11 subjects aged 24.5 ± 3.4 years; the

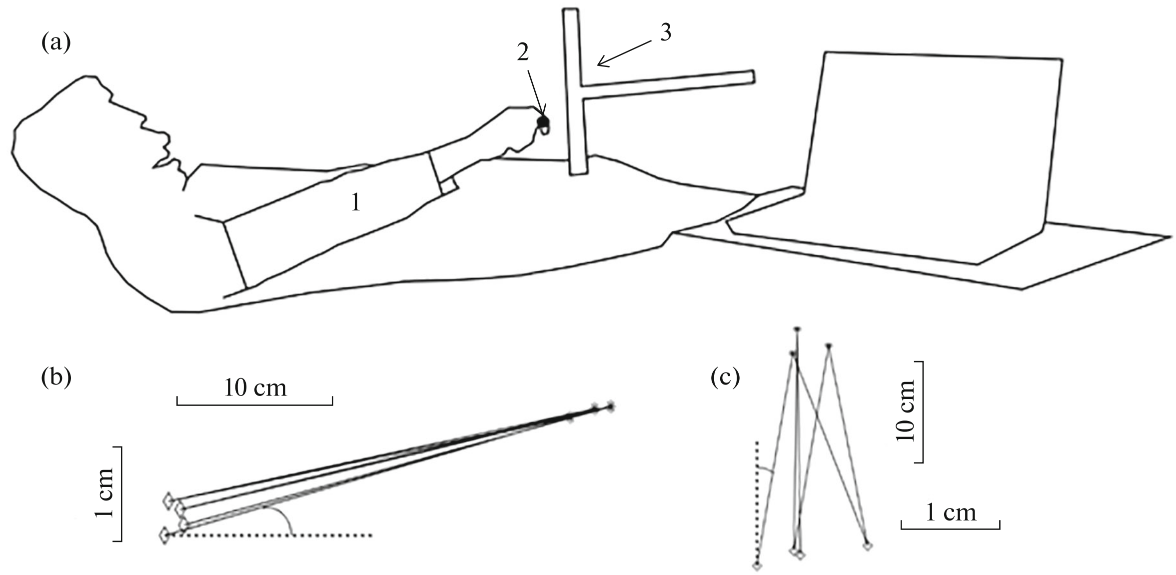

Fig. 1. Experiment design. (a) Subject position during the experiment. 1, elbow lock; 2, electromagnetic sensor; *3*, test segment. (b, c) An example of individual movements in assessing the horizontal (b) and vertical (c) segments. Angles with horizontal (b) and vertical (c) lines are marked.

group of subjects who were in a 5-day immersion (DI-5) included 14 men aged 31.2 ± 7.4 years. All studies were noninvasive and did not cause discomfort during the tests. The equipment complied with safety standards.

The measurements for the control group were carried out three times: on the first day, once (Background 1), on the second day, twice—in the morning (Background 2) and in the evening (Background 3). A similar measurement scheme corresponded to the group DI-6h cyclogram: measurements were performed before immersion (Background), during a 6-h immersion (DI-6h) after a 4-h exposure to immersion, and 2 h after the end of DI (R + 0). In group DI-5, measurements were taken before the start of DI (Background), on the 1st (DI1), 3rd (DI3), and 5th day (DI5) of DI, and after its end (R + 0). In the control group, as well as before and after DI, tests were performed on a couch in a standard semi-recumbent posture. When performing the test in DI, the tester was not required to be removed.

The dominant hand of the testers was determined according to the results of the Edinburgh questionnaire [15]. All testers performed the task with their dominant hand. The task of the tester was to carry out cyclic single-joint movements of the hand corresponding to the length and orientation of the presented segment for 5 s (Fig. 1a). Similarly to [4, 16], the hand performing the movement was always fixed during the test in a position that excluded movements at the elbow joint. In each experiment, four measurements were sequentially performed:

(1) The segment is oriented horizontally, eyes open.

(2) The segment is oriented horizontally,eyes closed.

(3) The segment is oriented vertically, eyes open.

(4) The segment is oriented vertically; eyes closed.

The segment length in all measurements was 20 cm.

A 3D Guidance trakSTAR electromagnetic system sensor (Ascension Technology Corporation, United States) with a sampling frequency of 80 Hz and a measurement error of 1.4 mm, which the subject held between the index finger and the thumb, was used to register a three-dimensional motion trajectory (Figs. 1b, 1c). The obtained trajectory was extrapolated by separate segments (their ends are marked with diamonds and asterisks in Figs. 1b, 1c) in the automated processing mode using the original software in the Matlab R2016b technical computing environment (Matworks Inc., USA). The length of each segment in Euclidean three-dimensional space, the time required by the subject for this movement, as well as the angle between this segment and the horizontal (Fig. 1b) or vertical (Fig. 1c) axis were determined. Further, the average length of the trajectory segment in this experiment, the average speed of movement as the ratio of the average length of this segment to the average time of hand movement, and the mean deflection angle from the corresponding axis were determined for all segments.

The sets of values obtained for each group within the conditions (horizontal or vertical segment, eyes open or closed) and measurement days were compared with each other using Student's t-test (if both sets of values were normally distributed according to the Lilliefors test) or using the Wilcoxon signed rank test (otherwise). The significance of differences between corresponding measurements made on different days or between measurements made on the same day, but under different conditions differing in the value of one parameter (for example, the "horizontal segment, eyes open" condition versus the "horizontal segment, eyes closed" condition) was estimated at $p < 0.05$ with Bonferroni's correction for the number of multiple comparisons. Data are presented as Mean ± Standard Deviation.

RESULTS

The *control* group subjects (Fig. 2) overestimated the presented segments equally, regardless of the condition and serial number of the experiment; the speed of their movements did not depend on the condition and the serial number of the experiment either. At the same time, the estimates of the direction of the horizontal segments were more accurate than the estimates of the directions of the vertical segments in all (Background1—Background3) measurements both under open and closed eyes condition (open eyes: 4.85° ± 4.84°, 3.03° ± 2.02°, 5.37° ± 4.68° vs. 21.85° ± 14.98°, 23.26° ± 17.56°, 23.81° ± 14.11° for Background1, Background2, Background3 measurements, respectively, $p < 0.01$; closed eyes: 5.41° ± 5.37°, 3.80° ± 3.62°, 5.49° ± 5.60° vs. 24.42° ± 11.39°, 26.20° ± 16.42°, 24.85° ± 16.01° for Background1, Background2, and Background3 measurements, respectively, $p < 0.01$).

The *experimental* group of DI-6h subjects (Fig. 3) also always overestimated the presented segments, and the degree of overestimation depended both on the condition and on the day of measurement. Before and after DI, the overestimation of horizontal segments with the eyes closed was lower than that of horizontal segments with eyes open and vertical segments with eyes closed (Background: 3.39 ± 3.74 cm vs. 7.12 ± 1.82 cm, $p < 0.01$ and 10.46 ± 3.49 cm, $p < 0.01$, respectively; R + 0: 4.41 ± 2.97 cm vs. 7.81 ± 3.24 cm, $p < 0.01$ and 9.71 ± 3.28 cm, $p < 0.001$, respectively). At the same time, before and after DI, the speed of hand movement along the horizontal segments with eyes closed was lower than along the horizontal segments with eyes open and along the vertical segments with eyes closed (Background: 0.23 ± 0.07 m/s vs. 0.27 ± 0.08 m/s, $p < 0.01$ and 0.29 ± 0.10 m/s, $p < 0.01$, respectively; R + 0: 0.26 ± 0.12 cm vs. 0.31 ± 0.14 m/s, $p < 0.05$ and 0.31 ± 0.13 m/s, $p < 0.01$, respectively). During DI, the overestimation of horizontal segments with closed eyes increased compared to the pre- and post-DI conditions (7.57 ± 2.74 cm vs. 3.39 ± 3.74 cm, $p < 0.05$ and 4.41 ± 2.97 cm, $p < 0.05$, respectively). Also, during DI, the error in estimating the direction of vertical segments both with eyes open and closed increased in relation to measurements performed after DI (5.47° ± 3.58° vs. 2.06° ± 1.56°, $p < 0.05$ and 7.56° ± 4.34° vs. 3.46° ± 2.49°, $p < 0.05$, respectively). Note that during DI, the error in estimating the direction of vertical segments with open eyes was lower than with closed eyes (5.47° ± 3.58° vs. 7.56° ± 4.34°, $p < 0.05$).

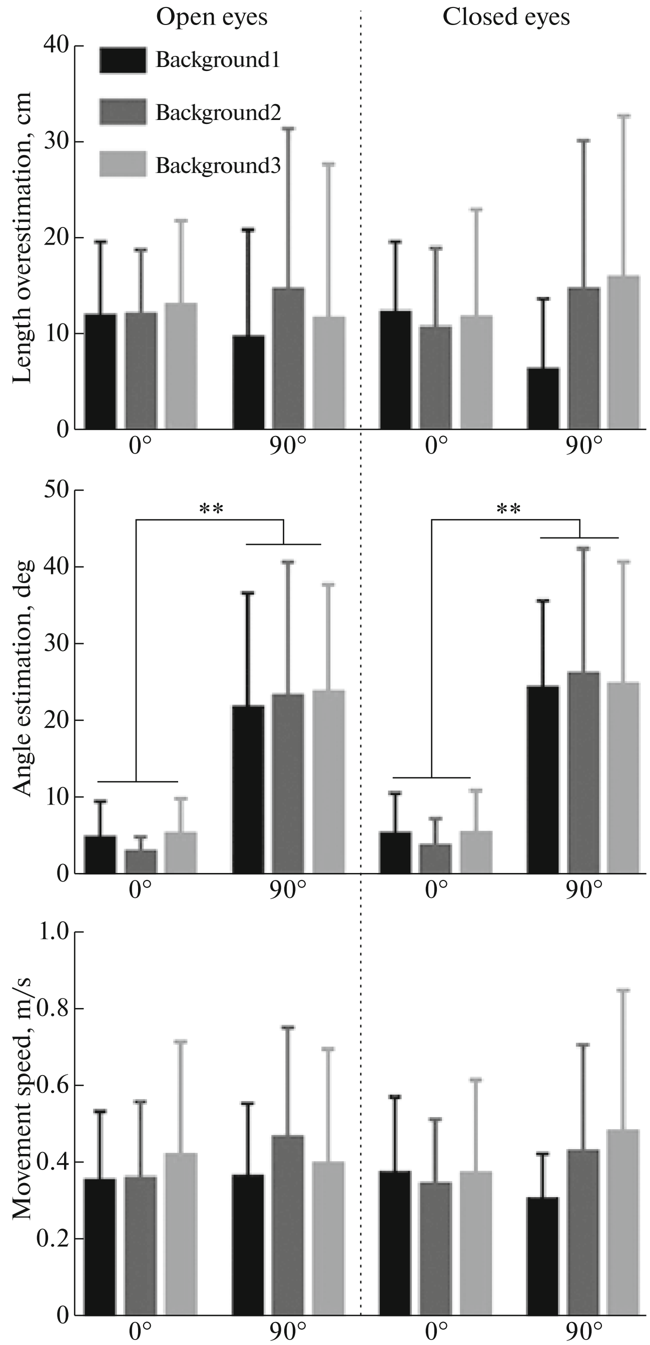

Fig. 2. The accuracy of hand movements of the control group subjects ($n = 10$). 0°, movement along horizontal segments, 90°, movement along vertical segments. **, $p < 0.01$. Mean ± Standard Deviation.

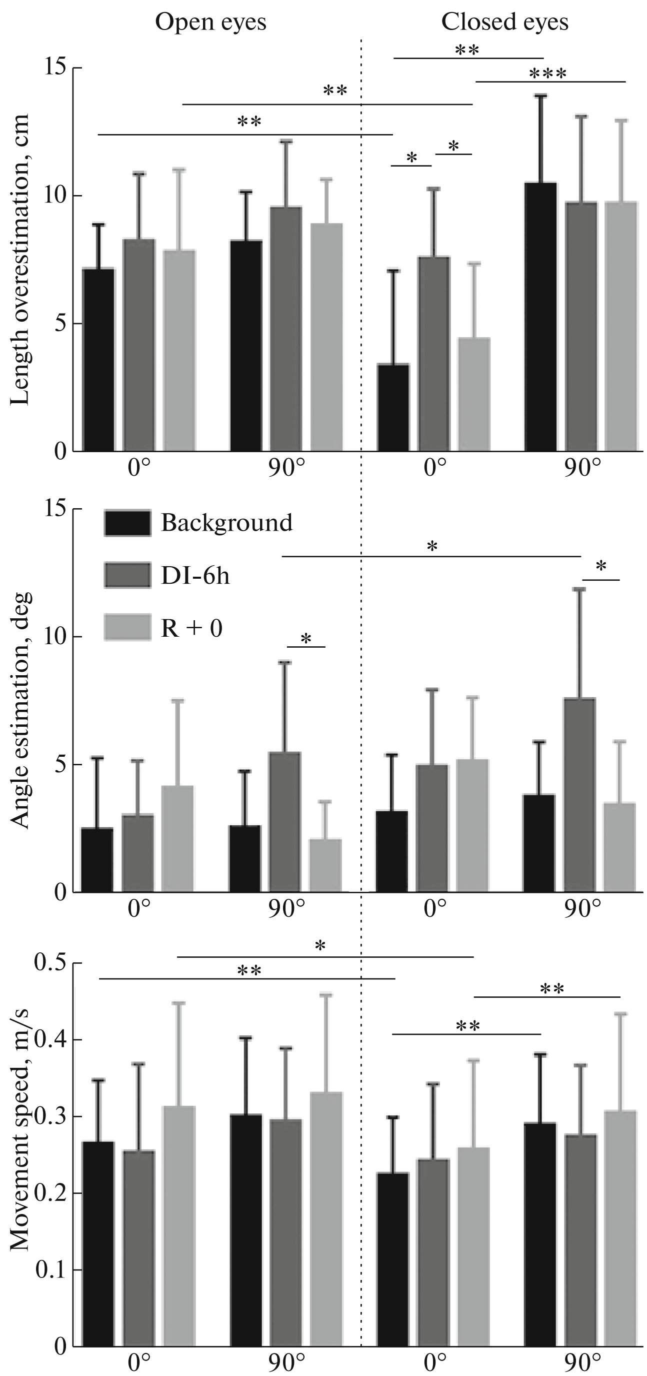

Fig. 3. The accuracy of hand movements of the subjects who were in the 6-h Dry Immersion (DI), in the background, during the immersion, and after it (R + 0) (n = 11). *, $p < 0.05$; ***, $p < 0.001$. See Fig. 2 for other designations.

The experimental group of DI-5 subjects (Fig. 4, Table 1) also overestimated the segments presented. Similar to the subjects from the previous group, the degree of overestimation of horizontal segments with eyes closed before DI was lower than with eyes open (5.75 ± 3.03 cm vs. 8.26 ± 2.51 cm, $p < 0.01$) and after the end of DI was lower than the degree of overestimation with closed eyes (6.50 ± 3.83 cm vs. 9.40 ± 5.87 cm, $p < 0.01$). At the same time, before and after DI, the speed of hand movement along the horizontal segments with eyes closed was lower than with eyes open (0.34 ± 0.11 m/s vs. 0.41 ± 0.13 m/s, $p < 0.01$ and 0.35 ± 0.10 m/s vs. 0.40 ± 0.10 m/s, $p < 0.01$, respectively). Prior to DI, the error in estimating the direction of horizontal segments with eyes closed was higher than with eyes open (3.39° ± 2.38° vs. 1.51° ± 1.18°, $p < 0.01$). On the first day of DI, the error in estimating the direction of vertical segments with the eyes open was higher than before DI and on the fifth day of DI (5.38° ± 9.65° vs. 1.23° ± 1.63°, $p < 0.001$ and 1.45° ± 0.98°, $p < 0.01$).

DISCUSSION

Overestimation of reproducible segments (hypermetry) observed in all three groups seems to be more typical of cyclic movements used in [17] than of single ones during which, without visual feedback, the amplitude of movement is underestimated [18]. It may be suggested that the subjects considered the proposed task to be quite simple and adhered to the following strategy: first they classified the segment as horizontal or vertical [19] and then reproduced it based more on proprioception than on visual information. Therefore, the degree of segment overestimation in the control group did not depend on whether or not the subject had access to visual feedback. Slight complication of the task (eyes closed) led to the fact that the subjects from the experimental groups performed movements along horizontal segments in the background (groups DI-6h and DI-5) and after the end of DI (group DI-5) more slowly than with eyes open. Such a decrease in the speed of movements allowed them to control the length of the hand movement more effectively, which decreased the degree of overestimation of the length (but not direction) of horizontal segments outside of DI. The presented results may also be linked to an increase in the efficiency of learning processes with the complication of irrelevant components of the task [20]. In this case, visual feedback (the factor of open or closed eyes) is indirectly associated with the learning of a movement corresponding to the length of a vertically or horizontally oriented segment. Moreover, length estimation itself could be considered by the subject as a secondary task in relation to segment orientation estimation (the orientation changed, but the length did not). Such results are typical of a large number of cognitive tasks in various modalities, which is explained by the laws of the work of consciousness.

In general, the reproduction of vertical segments led to more serious errors than the reproduction of horizontal segments (more serious direction error for all sessions of experiments in the control group; larger segment length overestimation with the eyes closed before and after DI in group DI-6h, as well as after DI in group DI-5). This can be explained by the fact that, unlike horizontal movements the direction of which is perpendicular to the gravity vector, the direction of cyclic vertical movements is either codirected or opposite to the gravity vector [21].

The overestimation of the vertical segment length during movements with eyes closed, when the action is carried out from memory using the visual information of the ventral stream [22], may also be influenced by the general tendency to overestimate the vertical segment compared to the horizontal one, which is one of the factors in the appearance of a visual vertical-horizontal illusion [23, 24]. During DI, the differences between the overestimation of horizontal and vertical segments disappear, which may indirectly indicate a change in the perception of the vertical during gravitational unloading. Changes in a similar direction were also observed in other experimental paradigms: microgravity during parabolic flight reduces the strength of the vertical–horizontal illusion to the greatest extent [25], cubes flatten when they are drawn with eyes closed under SF conditions [26], acute cognitive stress affects cyclic hand movements in the vertical, but not the horizontal plane [27].

In the control group, the parameters under consideration did not depend on the measurement number; therefore, the increase in the degree of segment length overestimation and errors in estimating segment direction observed in both experimental groups are associated with the fact that the subjects were under DI conditions, but not with the potentially nonlinear dynamics of learning to perform an unusual motor task. The presence of such errors, which are qualitatively similar to those observed in parabolic [16] and space [4] flight conditions, as well as in microgravity modeled using technical devices [28], indicates the validity of the DI model for studying the accuracy characteristics of hand movements. Presumably, a decrease in the inflow of support, tactile, and proprioceptive afferentation due to a decrease in muscle activity and support unloading changes the nature of the functioning of multisensory vestibular nuclei, which is accompanied by a change in the central intersensory interactions [13] reducing the quality of precise hand movement performance.

The use of a ground-based model of gravitational unloading made it possible, firstly, to recruit a sufficiently large sample of subjects ($n > 10$ in each group); secondly, to carry out measurements for all s with the same frequency, which is often difficult under SF conditions; and, thirdly, to conduct longitudinal studies, which are impossible, for example, with the use of the parabolic flight paradigm. As a result, it can confidently be asserted that impairments in the performance of the proposed cyclic motor tasks are limited to the first day of DI (errors in estimating the vertical segment direction with open eyes for group DI-5), which agrees well with the observations that movement precision deteriorates to the greatest extent in the initial period of adaptation to the change in gravity to return then to the initial values [29]; orientation illusions, which testify to the gradual process of the astronaut's adaptation to microgravity, are also most pronounced in the first hours of flight [3]. Adaptation to the performance of other, discrete, visuomotor tasks, in which, presumably, other mechanisms for con-

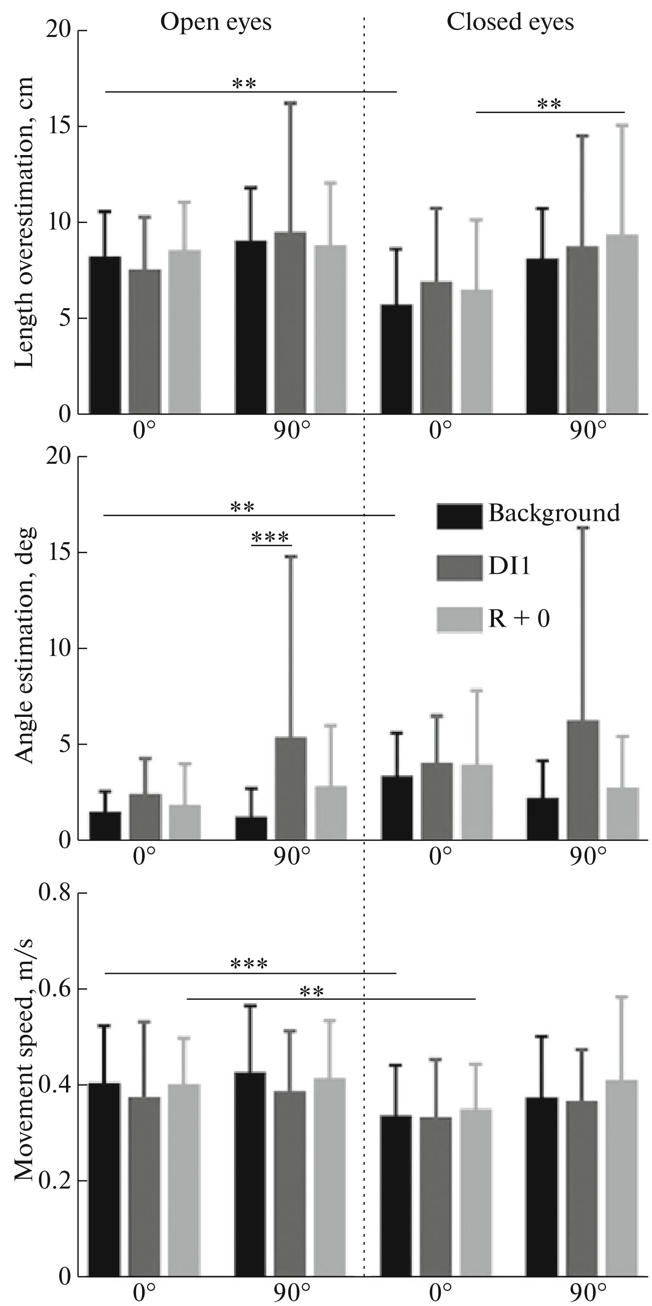

Fig. 4. The accuracy of hand movements of the subjects who were in the 5-day Dry Immersion (DI), in the background, on the first day of immersion and after its completion (R + 0) ($n = 14$). ***, $p < 0.001$. See Fig. 2 for other designations.

Table 1. The accuracy of hand movements of the subjects who were in a 5-day Dry Immersion (DI) on the 3rd and 5th days of immersion ($n = 14$)

DI duration	Open eyes		Closed eyes	
	0°	90°	0°	90°
	Length overestimation, cm			
DI3	7.33 ± 3.30	7.63 ± 2.74	8.29 ± 5.05	7.99 ± 5.12
DI5	6.64 ± 5.15	8.29 ± 2.92	7.61 ± 4.90	8.43 ± 3.55
	Angle estimation, deg			
DI3	2.03 ± 1.57	2.04 ± 1.60	3.36 ± 2.22	2.29 ± 2.47
DI5	4.06 ± 9.77	1.44 ± 0.98	3.14 ± 2.45	2.24 ± 1.28** from DI1
	Movement speed, m/s			
DI3	0.36 ± 0.12	0.37 ± 0.12	0.33 ± 0.11	0.38 ± 0.13
DI5	0.35 ± 0.15	0.41 ± 0.14	0.32 ± 0.11	0.37 ± 0.13

0°, movement along horizontal segments; 90°, movement along vertical segments. **, $p < 0.01$. Mean ± Standard Deviation.

trolling hand movements are recruited [30], may be more time consuming. Thus, the characteristics of visual-manual tracking are variable throughout the entire 7-day DI [13] and decrease on the 3rd and 5th days of the 5-day DI [31]; the strength of the Müller–Lyer illusion during its motor assessment decreases on the 5th day of the 5-day DI [32] and on the 10th day of the 21-day DI [33].

The selectivity of the influence of both experimental conditions and DI on the degree of segment length overestimation or on movement direction estimation indirectly indicates the predominant vector coding of dominant hand movements [34, 35]. Note that within the framework of such coding at the stage of movement planning, movement direction and amplitude are presented separately [14, 35].

CONCLUSIONS

(1) The effect of DI of different duration (6 h, 5 days) on cyclic hand movements reproducing the length and orientation of horizontal and vertical segments was studied in the presence and absence of visual feedback. It has been shown that the task of estimating vertical segments is accompanied by more serious errors than the task of estimating horizontal ones. While the accuracy of movements of the control group subjects did not depend on the measurement number, that of the volunteers who were in DI decreased on the 1st day of DI: both the overestimation of the length of the horizontal segments and the error in estimating the direction of the vertical segments increased.

(2) The data obtained convincingly indicate that being in DI affects not only the work of the postural-tonic system, but also the control system of hand movements. Thus, DI can be considered as a suitable ground-based model for studying fine movement disorders observed in microgravity.

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COMPLIANCE WITH ETHICAL STANDARDS

All procedures performed in studies involving human participants were in accordance with the biomedical ethics principles formulated in the 1964 Helsinki Declaration and its later amendments and approved by the Biomedical Ethics Committee of the Institute of Biomedical Problems, Russian Academy of Sciences (Moscow) (Protocol no. 401 of July 15, 2015; no. 432 of September 14, 2016).

Conflict of interest. The authors declare that they have no conflict of interest.

Informed consent. Each study participant provided a voluntary written informed consent signed by him after explaining to him the potential risks and benefits, as well as the nature of the upcoming study.

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