Changes in posture following a single session of long-duration water immersion

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Abstract:

Transitioning between different sensory environments is known to affect sensorimotor function and postural control. Water immersion presents a novel environmental stimulus common to many professional and recreational pursuits, but is not well-studied with regard to its sensorimotor effects upon transitioning back to land. The authors investigated the effects of long-duration water immersion on terrestrial postural control outcomes in veteran divers. Eleven healthy men completed a 6-hour thermoneutral pool dive (4.57 m) breathing diver air. Center of pressure was observed before and 15 minutes after the dive under 4 conditions: (1) eyes open/stable surface (Open-Stable); (2) eyes open/foam surface (Open-Foam); (3) eyes closed/stable surface (Closed-Stable); and (4) eyes closed/foam surface (Closed-Foam). Postdive decreases in postural sway were observed in all testing conditions except for Open-Stable. The specific pattern of center of pressure changes in the postdive window is consistent with (1) a stiffening/overregulation of the ankle strategy during Open-Foam, Closed-Stable, and Closed-Foam or (2) acute upweighting of vestibular input along with downweighting of somatosensory, proprioceptive, and visual inputs. Thus, our findings suggest that postimmersion decreases in postural sway may have been driven by changes in weighting of sensory inputs and associated changes in balance strategy following adaptation to the aquatic environment.

Keywords: diving | postural control | vestibular | sensory reweighting

Article:

Strategies for postural control are dependent on integrated sensory input (ie, sensor fusion) from the somatosensory and vestibular systems, primarily mediated by the latter 2 under normal environmental conditions in healthy individuals.[1] Exposure to novel environments in which sensory input does not match previously recognized stimulus patterns and/or stored postural control strategies creates "sensory conflict" and can result in postural ataxia.[2,3]

A well-researched example of sensory conflict occurs when an individual returns to a terrestrial environment after prolonged exposure to a microgravity environment (eg, space flight where Earth's gravitational vector is reduced or absent). Microgravity conditions are thought to be associated with a decreased reliance on vestibular input and an increased reliance on visual and proprioceptive input.[4] This "reweighting" of sensory input is "adaptive" for space flight, but has been shown to be maladaptive for the terrestrial environment encountered afterward and results in postural ataxia up to 9 days following space flight.[4] Given the similarities between aquatic and microgravity environments, it is reasonable to suspect that water immersion may also result in sensory conflict and subsequent postural ataxia.

Water immersion is similar to microgravity in that both involve withdrawal of support, reduced weight, pressure changes, fluid shifts, and changes in muscle tone.[5,6] However, it differs from microgravity in that it provides a form of continuous multimodal stimulation. This stimulation engages tactile, pressure, and thermal-sensitive receptors uniformly throughout the body depending on changes in physical characteristics such as buoyancy, hydrostatic pressure, and temperature.[7,8] Continuous whole-body stimulation and concurrent decreases in weight and muscle tone are thought to diffuse the amount and quality of somatosensory and proprioceptive afferent input.[9] Degradation of proprioceptive input can ultimately result in increases in both reaction time and isometric force production,[10] either of which can adversely affect posture and balance.[11,12]

Differences between microgravity and aquatic environments also affect visual and vestibular sources of input. Unlike microgravity, human vision is adversely impacted during water immersion, as air is replaced by water at the corneal surface producing a gross hypermetropia (ie, images become severely blurred and unfocused) and the eye loses about two-thirds of its refractive power.[13,14] Diving masks restore the air-to-cornea interface allowing for high underwater acuity; however, they produce a refraction at their outer surface, which results in a narrowing of the visual field, magnification of objects, and distortion of verticals and horizontals.[14]

While gravitational forces acting on the vestibular system are comparable in aquatic and microgravity environments,[15] water immersion does result in a blunting of linear/angular head velocities and accelerations. This is due to the increased density of the surrounding medium, which decreases stimulation of the semicircular canals and otolith organs.[16] Unfortunately, there is limited research determining if the changes in sensory function that occur during water immersion are maintained after the transition to a terrestrial environment. More importantly, the extent to which any observed changes are maladaptive for the terrestrial environment is unknown.

Postural control is a commonly observed outcome in the assessment of sensorimotor function and spatial orientation.[17] In healthy adults and under normal conditions, characteristic postural sway occurs both in the anteroposterior and mediolateral directions.[18] Assessments of postural control are sensitive to neurophysiological deficits, such as those stemming from aging or disease,[19] as well as changes in the profile of sensory information provided by the environment.[3] Few studies have investigated the influence of water immersion on postural control in general. Furthermore, the focus among them is limited to postural sway while immersed,[20] comparisons between aquatic and land-based assessments,[21–23] or postural control following water-based exercise interventions.[24,25] In contrast, the purpose of this study was to examine the effects of long-duration exposure to underwater immersion on static, terrestrial postural control in a sample of veteran divers. Two hypotheses were formulated: (1) that a single long-duration exposure would be associated with increases in postural sway (postural ataxia) upon surfacing from the dive and (2) the increases in postural sway would be most apparent under conditions of sensory conflict.

Methods

Subjects

Eleven male divers (30.9 [6.1] y, 86.2 [11.8] kg, 182.6 [5.3] cm) participated in this study. All participants were Navy divers on full-time active duty orders with no recent injuries or history of medical conditions affecting balance control. Prior to data collection, subjects provided written informed consent to participate in this protocol, approved by the Navy Experimental Diving Unit (NEDU) institutional review board in Panama City, FL.

Procedures. The present study was conducted as part of a larger research project examining the neurophysiological response to repeated diving under a variety of conditions.[7,26] Participants completed a 6-hour dive once daily for 5 days with outcome measures collected before and after each dive. The analyses presented in this manuscript were limited to data collected during the first day (ie, immediately before and after the first dive exposure) so as to avoid effects related to training, learning, or chronic adaptation. All data were collected at the NEDU test facility. Center of pressure (COP) data were recorded during a series of static balance trials one day before (pretest) and no more than 15 minutes after a 6-hour dive (posttest). All subjects completed a familiarization session prior to data acquisition. Balance testing was performed in a dry, laboratory environment under ambient conditions. Prior to postdive testing, subjects were allowed to dry themselves and change into dry clothing with the exception of shoes and socks, which were not permitted during the trials.

Dives were performed with subjects wearing a T-shirt and shorts in a temperature-controlled test pool (4.57 m deep) at the NEDU facility. Water temperature ranged from 32°C to 33°C so as to maximize comfort during immersion with intermittent exercise. Participants remained at the bottom of the test pool (4.57 m deep) with the lung centroid at a pressure equivalent to 1.35 atmospheres absolute for the duration of the dive. Weight belts were used to maintain slightly negative buoyancy. Participants alternated between six 30-minute periods of rest in a prone position and six 30-minute periods of exercise. For the rest periods, the participants were instructed to sit completely still and remain quiet. For the exercise periods, a custom underwater ergometer was initially set to a load of 50 W (equivalent to about 115 W in air) and was adjusted to maintain a target heart rate of 95 (5) beats per minute. A surface-supplied MK20 underwater breathing apparatus (UBA; Interspiro, Inc, Point Pleasant, WI) supplied diver air (78% nitrogen, 21% oxygen) with positive pressure ventilation to minimize hydrostatic breathing resistance. After 3 hours, subjects surfaced briefly (~10 min) for a standardized lunch break in chest-deep water.

Data Collection and Processing. For balance testing, subjects were instructed to remain as motionless as possible during three 70-second trials of double-leg quiet stance in 4 conditions—eyes open/stable surface (Open-Stable), eyes open/foam surface (Open-Foam), eyes closed/stable surface (Closed-Stable), and eyes closed/foam surface (Closed-Foam). Similar conditions are used in other posturography tests, such as clinical test of sensory interaction and balance.[27]

Ground reaction force data were collected at a frequency of 30 Hz using a Wii Balance Board (Nintendo Co, Kyoto, Japan) with custom data acquisition software written in MATLAB R2013a (MathWorks Inc, Natick, MA). All data reduction was performed in LabVIEW 2014 (National Instruments, Austin, TX). The COP time series were calculated for the anteroposterior (AP) and mediolateral (ML) directions from the raw force data during the middle 30 seconds of each trial. Additional processing of COP data was performed to compute the desired metrics of postural control. First, COP ranges for the AP and ML time series were calculated as the difference between the maximum and minimum displacement values in each respective direction. Second, mean COP velocity for the AP and ML time series were calculated. Third, path length (Path Length) was calculated by summing the change in distance of the AP and ML vectors at each successive time point.

Statistics. Multiple 2 × 4 (time [pretest or posttest] × condition [Open-Stable, Open-Foam, Closed-Stable, and Closed-Foam]) repeated-measures analyses of variance (ANOVA) were used to examine the effects of long-duration underwater exposure on each dependent variable (Path Length, AP Range, ML Range, AP velocity, and ML velocity). Significant main effects for time and significant interactions time × condition were followed by univariate tests. Planned dependent *t* tests were then performed for all outcomes. Effect sizes were reported as partial eta-squared:

$$\eta^2 = \frac{\mathrm{SS}_{\mathrm{effect}}}{\mathrm{SS}_{\mathrm{effect}} + \mathrm{SS}_{\mathrm{error}}} \tag{1}$$

and interpreted using previously published guidelines for eta-squared indices: .04 = small effect, .25 = medium effect, and .64 =large effect.[28] Planned pairwise comparisons were performed for Time pairings for all dependent variables. Effect sizes were estimated using Cohen's *d* corrected for within-subjects designs using the average SD of both of the repeated measures as a standardizer:

$$d_{\mathrm{av}} = \frac{M_{\mathrm{diff}}}{\sqrt{\frac{\mathrm{SD}_1 + \mathrm{SD}_2}{2}}} \tag{2}$$

for each condition and interpreted using previously published guidelines for group differences: for d_{av}, 0.2 = small effect, 0.5 =medium effect, and 0.8 = large effect. Finally, in order to provide context regarding whether any observed changes may be clinically meaningful, we also present clinical significance as a change from the predive mean >1 SD.[29,30]

Alpha was set *a priori* at .05 for all statistical tests. Adjustments for multiple comparisons were not made in order to avoid an overly conservative outlook for detecting differences.[31] All statistical analyses were conducted using IBM SPSS Statistics (version 23.0; IBM Corp, Armonk, NY).

Results

With the exception of AP Range in the Open-Stable condition, all postdive outcomes were lower than their predive counterparts (Table 1).

Table 1. Descriptive Statistics for the Outcome Measures

			Pre		Post			Delta					
Condition	**Metric, cm**	**n**	**Mean**	**SD**	**Mean**	**SD**	**% change**	**Mean**	**SD**	**SE**	***t*statistic**	**ES**	**CS**
Open-Stable	AP Range	11	1.88	0.51	1.98	0.39	5	0.10	0.45	0.13	0.74	0.22	NS
	AP Vel	11	0.85	0.14	0.79	0.09	−7	−0.06	0.11	0.03	−1.86	−0.52^{a}	NS
	ML Range	11	1.14	0.31	1.03	0.24	−9	−0.11	0.43	0.13	−0.82	−0.39	NS
	ML Vel	11	0.71	0.07	0.67	0.09	−6	−0.04	0.07	0.02	−1.79	−0.50^{a}	NS
	Path Length	11	36.07	4.41	33.68	3.41	−7	−2.39	3.98	1.20	−1.99	−0.61^{a}	NS
Closed-Stable	AP Range	11	2.80	0.54	2.30	0.61	−18	−0.50	0.67	0.20	−2.45*	−0.86^{b}	NS
	AP Vel	11	1.32	0.35	1.08	0.23	−18	−0.24	0.22	0.07	−3.57*	−083^{b}	NS
	ML Range	11	1.37	0.33	1.09	0.28	−20	−0.28	0.39	0.12	−2.39*	−0.92^{b}	NS
	ML Vel	11	0.82	0.14	0.72	0.13	−12	−0.10	0.11	0.03	−3.10*	−0.74^{a}	NS
	Path Length	11	49.94	11.49	41.70	7.25	−16	−8.24	7.94	2.40	−3.44*	−0.88^{b}	NS
Open-Foam	AP Range	11	3.27	1.01	3.15	0.70	−4	−0.12	0.66	0.20	−0.60	−0.14	NS
	AP Vel	11	1.44	0.38	1.33	0.28	−8	−0.11	0.32	0.10	−1.12	−0.33	NS
	ML Range	11	2.63	0.97	1.99	0.41	−25	−0.65	0.63	0.19	−3.40*	−0.93^{b}	NS
	ML Vel	11	1.09	0.22	0.91	0.08	−17	−0.18	0.21	0.06	−2.82*	−1.20^{b}	NS
	Path Length	11	58.78	13.93	52.34	7.28	−11	−6.44	11.88	3.58	−1.80	−0.61^{a}	NS
Closed-Foam	AP Range	11	5.75	0.92	5.27	0.94	−8	−0.48	0.73	0.22	−2.18	−0.52	NS
	AP Vel	11	2.80	0.41	2.47	0.41	−12	−0.33	0.27	0.08	−4.13*	−0.80^{b}	NS
	ML Range	11	3.46	0.87	3.09	0.68	−11	−0.36	0.41	0.12	−2.92*	−0.47	NS
	ML Vel	11	1.55	0.31	1.35	0.23	−13	−0.20	0.22	0.07	−3.07*	−0.74^{a}	NS
	Path Length	11	103.42	14.13	90.80	12.79	−12	−12.62	9.16	2.76	−4.57*	−0.94^{b}	NS

Abbreviations: AP, anteroposterior; COP, center of pressure; CS, clinical significance; Delta, mean difference; ES, effect size (Cohen's d_{av}); ML, mediolateral; Path Length, total resultant COP displacement; Vel, velocity. Note: Predive and postdive data are shown for each variable. Outcomes were calculated using a 30-second COP time series created from the raw signal sampled at 30 Hz.

^{a}ES exceeds cutoff for "medium" ($d \geq 0.50$). ^{b}ES exceeds cutoff for "large" ($d \geq 0.80$).

*Significant compared with baseline data.

For COP Path Length, the results of the ANOVA indicated a significant main effect for time ($F_{1,10} = 20.69$, $P < .05$, η2p=.67) and a significant time × condition interaction ($F_{3,30} = 3.18$, $P <.05$, η2p=.24). Pairwise comparisons for time revealed that the mean for the postdive was significantly smaller than the predive (mean difference = −7.42, SE = 1.63, $P \leq .001$). Planned paired *t* tests revealed that the time × condition interaction for Path Length was driven by significant 16% and 12% decreases in the Closed-Stable and Closed-Foam conditions, respectively; however, none of these decreases were found to have clinical significance.

For COP AP Range, the ANOVA revealed a significant time ×condition interaction ($F_{3,30} = 2.92$, $P = .05$, η2p=.23). Planned paired *t*tests revealed that the time × condition interaction for AP Range was driven by significant 18% decrease for the Closed-Stable condition; however, this decrease was not found to have clinical significance.

For COP ML Range, the ANOVA revealed a significant main effect for time ($F_{1,10} = 17.55$, $P \leq .05$, η2p=.64) and significant time × condition interaction ($F_{3,30} = 2.80$, $P \leq .05$, η2p=.22). Pairwise comparisons for time revealed that the mean for the postdive was significantly smaller than the mean for the predive (mean difference = −0.35, SE = 0.083, $P \leq .05$). Planned paired *t* tests revealed that the time × condition interaction for COP ML Range was driven by significant 20%, 25%, and 11% decreases in the Closed-Stable, Open-Foam, and Closed-Foam conditions, respectively; however, none of these decreases were found to have clinical significance.

For COP AP velocity, the ANOVA revealed a significant main effect for time ($F_{1,10} = 20.90$, $P \leq .05$, η2p=.68) and significant time × condition interaction ($F_{3,30} = 2.96$, $P \leq .05$, η2p=.23). Pairwise comparisons for time revealed that the mean for the postdive was significantly smaller than the mean for the predive (mean difference = −0.18, SE = 0.04, $P \leq .05$). Planned paired *t* tests revealed that the time × condition interaction for COP AP velocity was driven by significant 18% and 12% decreases in the Closed-Stable and Closed-Foam conditions, respectively; however, none of these decreases were found to have clinical significance.

For COP ML velocity, the ANOVA revealed a significant main effect for time ($F_{1,10} = 14.59$, $P \leq .05$, η2p=.59) and significant time × condition interaction ($F_{3,30} = 3.42$, $P \leq .05$, η2p=.26). Pairwise comparisons for time revealed that the mean for the postdive was significantly smaller than the mean for the postdive (mean difference = −0.14, SE = 0.03, $P \leq .05$). Planned paired *t* tests revealed that the time × condition interaction for COP ML velocity was driven by significant 12%, 17%, and 13% decreases in the Closed-Stable, Open-Foam, and Closed-Foam conditions, respectively; however, none of these decreases were found to have clinical significance.

Discussion

The purpose of this study was to examine the effects of long-duration exposure to underwater immersion on static terrestrial postural control in a sample of veteran divers. To our knowledge, no previous study has investigated the effects of a single thermoneutral long-duration water immersion on postural control. Our main finding was that postural sway is significantly decreased relative to baseline following a single thermoneutral long-duration water immersion. While effect sizes for postural control outcomes ranged from small to large, we were not able to conclude that any of the observed changes were clinically meaningful using conventional thresholds.

The observed changes in postural control were most apparent when normal sensory information was not fully available, that is, all conditions except Open-Stable (Figure 1). There were significant mean reductions of medium effect for postural sway, velocity, and Path Length of 17%, 13%, and 13% from predive to postdive sessions, for the Closed-Stable, Open-Foam and Closed-Foam conditions, respectively. We discuss these predive to postdive differences in postural control in the context of (1) adaptation to the aquatic environment and associated changes in body segment coordination (ie, balance strategy) and/or (2) a reweighting of sensory input (ie, sensory integration/fusion).

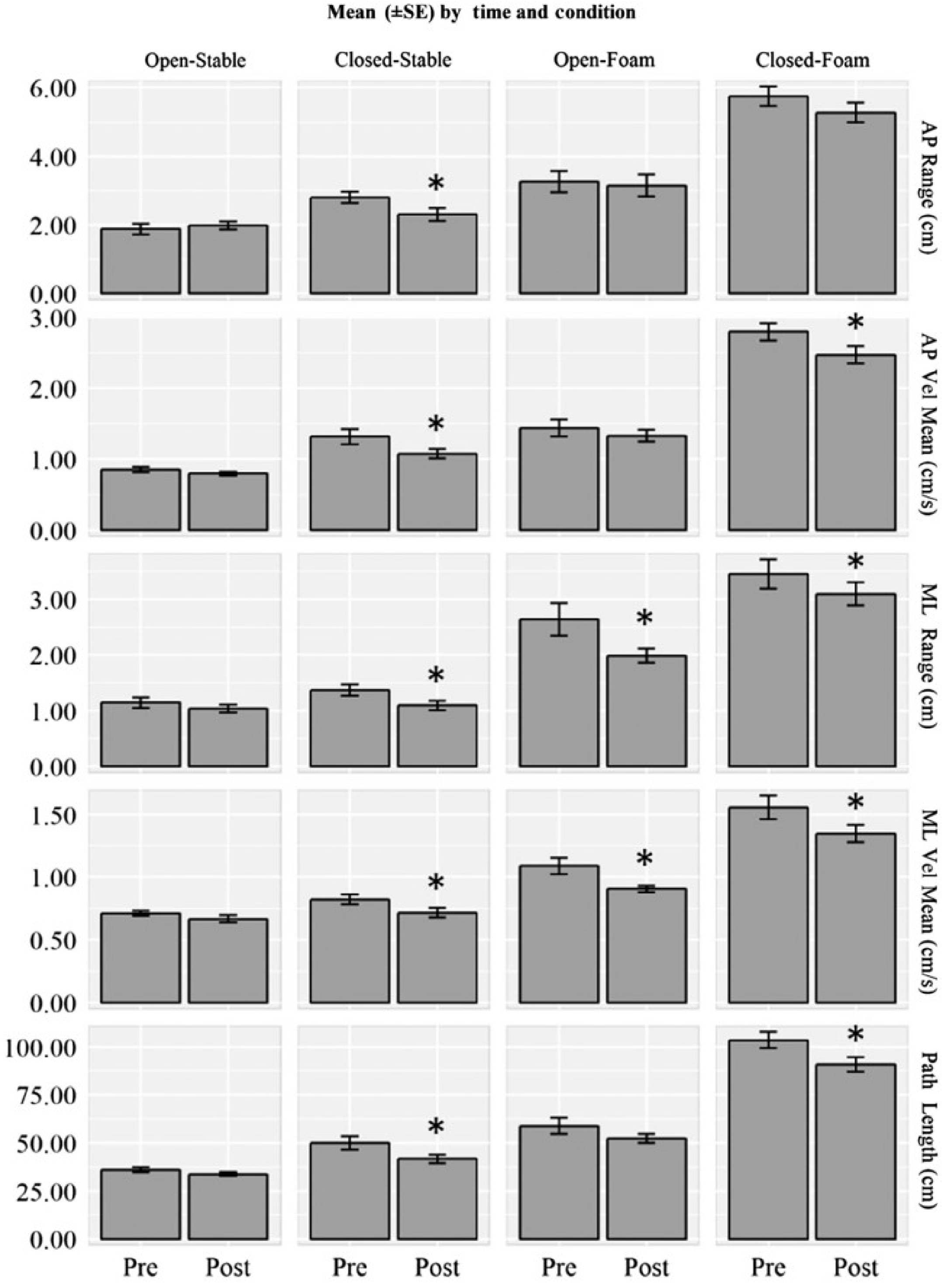

Figure 1. Predive and postdive means for each condition/outcome. Path Length indicates total resultant COP displacement; AP, anteroposterior; ML, mediolateral; Vel, velocity. *Significant compared with baseline data.

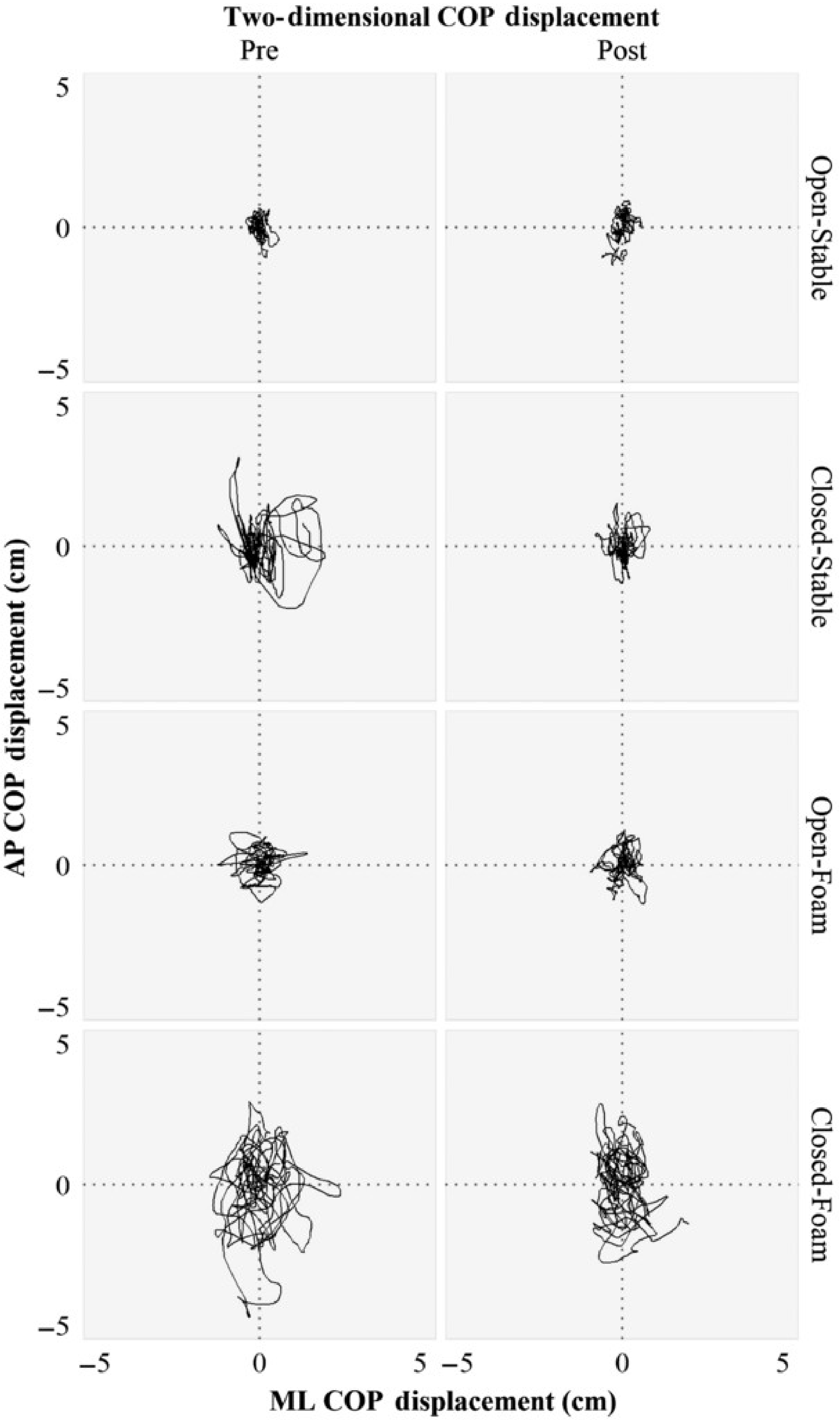

Figure 2. Two-dimensional COP traces for a representative subject. Predive COP (left) is shown alongside postdive COP (right) for each condition. AP indicates anteroposterior; COP, center of pressure; ML, mediolateral.

It is possible that our experimental treatment had an influence on postural control strategy. Healthy individuals typically stabilize their center of mass using either a hip strategy or an ankle strategy.[32] The ankle strategy predominates during quiet standing and is characterized by a limited capacity for corrective torque.[1,33] In contrast, a hip strategy may be evoked where greater corrective torque is required, such as during conditions involving changes in support surface or sensory information.[34] The 2 strategies are not mutually exclusive, but rather describe a continuum of possible postural control strategies.[34,35]

Multiple mechanisms of change in balance strategy may be relevant when considering our results. Changes in hydrostatic pressure and buoyancy that occur during water immersion result in an underloading condition which effectively reduces the corrective torque required to maintain equilibrium.[20,23] Ultimately, this may result in a shift toward an ankle strategy, which would be associated with greater AP Range of COP displacement[36] much like we observed (Figure 2). It is possible that this effect influenced AP COP Range for the unaltered sensory condition in our results. Although not significant, this was the only outcome in our study that increased in the postdive session and would be consistent with a shift toward an ankle strategy. Conversely, postdive AP COP Range means were lower in all other conditions (Closed-Stable $P < .05$). It is therefore possible that the combination of altered sensory conditions and the aquatic-to-terrestrial environmental transition encouraged ankle joint stiffening as might be expected during the perception of a postural threat.[37,38] Follow-up work including kinematic and additional kinetic measurements, particularly shear force, may be warranted to test these conjectures.

The observed differences in postdive postural control may stem from changes in how sensory input from the visual, vestibular, and proprioceptive systems are integrated and/or weighted. It has been suggested that the central nervous system can selectively and dynamically reweight different sensory modalities by: (1) decreasing its weight when sensory information from one or more sensory systems is unavailable or becomes unreliable and/or (2) increasing its weight on sensory inputs that provide accurate and reliable information.[3,39,40] Previous research has reported that water immersion affects cortical processing of somatosensory information.[41] It has also been reported that proprioceptive input is degraded during underloading conditions due to reductions in Golgi tendon organs, muscle spindles, visceral masses, and tactile and load receptors solicitation[42,43] and that input from the vestibular and visual systems is upweighted to compensate.[44] These compensatory changes are likely separate from, and complementary to, the aforementioned vestibular sensitization that results more directly from water's effect in blunt acceleration.[16] With the decreases in postural sway being most apparent in the no-vision conditions (Closed-Stable and Closed-Foam), it is feasible that vestibular input was upweighted to compensate for the degradation of somatosensory, proprioceptive, and visual input that occurs during water immersion.

This study was not without limitations. First, the present findings are specific to postural control and should be considered with respect to the timeframes used in this study. Additionally, diving is associated with a number of other physiological changes which may affect postural control. These include changes related to learning effects, fatigue, dehydration, blood chemistry, body temperature, barometric pressure, and gas mixture. Each of these potential confounds was controlled for to the extent possible at the NEDU test facility. Specifically, excessive learning (and/or practice) effects were prevented by comparing baseline data to postdive data sampled after the first dive only. Divers breathed ambient air while fatigue and dehydration were minimized through passive bottom time—including positive pressure ventilation—and standardized nutrition/hydration. Body temperature was regulated through temperature control of the test pool. Finally, while it is impossible to rule out the influence of blood chemistry or barometric pressure changes, a maximum depth within no-decompression limits (4.57 m, approximately 15 ft) minimizes these effects. These controls therefore increase the likelihood that the observed changes in balance outcomes were related to changes in the availability of sensory information.

In conclusion, we examined terrestrial quiet-standing postural control outcomes in veteran divers before and after long-duration water immersion in 4 conditions: (1) Open-Stable, (2) Open-Foam, (3) Closed-Stable, and (4) Closed-Foam. With the exception of the Open-Stable condition, postural sway motion was decreased after water immersion. We interpret these observations as being consistent with an acute sensory reweighting response and concomitant overregulation of postural control via the ankle strategy. Specifically, postdive postural control suggested upweighting of vestibular information accompanied by downweighting of somatosensory, proprioceptive, and visual inputs.

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