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OPTIMAL HYDROSTATIC LOADING FOR CLOSED-CIRCUIT UNDERWATER BREATHING APPARATUS DESIGN

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NOTICES

TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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During the course of 3 shallow air-saturation dives, over 100 man-dives were made to 29 fsw with closed-dircuit Underwater Breathing Apparatus (UBA) to test the effect of various hydrostatic loads on exercising divers. Both the MK-15 and EX-19 UBA were used. While in the erect sitting position, divers warmed-up for 5 min at 50 W, followed by 25 min of moderately heavy work (1.4 W/kg) on a submerged bicycle ergometer. Oxygen consumption, dyspnea score, and mouth pressure was continuously recorded. Three hydrostatic loads were presented to the divers by varying UBA position relative to the seated diver. Loads lay within and on either side of the current UBA hydrostatic loading specifications. All divers were able to complete work regardless of the hydrostatic load. and gave relatively low dyspnea scores. Subjectively, however, most divers preferred the median hydrostatic load, corresponding roughly to that at the suprasternal notch in an erect diver. The EX-19 UBA resulted in higher mouth pressures (DP) than the MK-15, which could be explained by the elastance of the EX-19. In spite of the higher DP, the EX-19 was preferred over the MK-15. The partitioning between inspiratory and expiratory pressure in both rigs was similar. Some divers prefer hydrostatic loads outside of the range of current specifications. Some bag designs, such as that of the EX-19, allow a diver more freedom in adjusting bag volume (and thereby hydrostatic loading) than do designs using shoulder mounted breathing bags.

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TABLE OF CONTENTS

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INTRODUCTION

Specifications for hydrostatic loading have been applied to the development of the Advanced Underwater Breathing Apparatus (AUBA), which is a closed-circuit, mixed-gas device designed for use by the special warfare community as a replacement for the MK-15. Specifications require that hydrostatic pressures lie between 0 and +10 cm H_20 relative to the suprasternal notch (SN) when the diver is in the prone or upright position.

Two prototypes for the AUBA were recently delivered to the Naval Experimental Diving Unit (NEDU) for testing. One was a prototype from the Naval Coastal Systems Center (NCSC). The second prototype was built by S-TRON, a division of Tekna. In their "Conventional Diving System (CDS), EX-19, Interim Report of Testing," NEDU stated "the S-TRON breathing bag placement resulted in negative hydrostatic pressure in most attitudes." During the initial manned testing at 14 fsw, divers complained of inspiratory breathlessness during light work. Accordingly, the S-TRON UBA was considered unsafe for further manned testing. The NCSC prototype, on the other hand, closely approached specifications and performed satisfactorily. The perception of both the NEDU testing team and NMRI investigators was that hydrostatic loading accounted for the marked differences in subjective impression of the two rigs.

The AUBA hydrostatic loading specifications were based upon the Middleton and Thalmann design goals (1981). Those goals were in turn based upon the demonstration that in a prone diver breathing bags located on the chest provided positive pressures which assist inspiration, while bags on the back caused negative pressure breathing, impeding inspiration (Flynn et al., 1975; Thalmann et al., 1979). Unfortunately, those same studies used experimental apparatus not directly applicable to operational diving. There has never been a detailed study of the effect of breathing bag placement on exercise tolerance in a UBA in current use in the fleet. Even comparisons between various types of UBA may not be suitable for comparing bag placement, because differences in breathing hoses and CO_2 canisters cause changes in breathing resistance, confusing the issue of bag location.

The purpose of this study was to review the role of breathing bag placement on diver work performance and comfort using an operational closed-circuit UBA. The MK-15 UBA served as a convenient and useful platform for evaluating the effects of hydrostatic loading. One NCSC prototype EX-19 was used for two days of comparison testing.

METHODS

Eighteen divers participated in a series of 3 shallow air-saturation dives at the Man-Rated Chamber Complex (MRCC) of the Naval Medical Research Institute. More than 100 man-dives were performed in association with this protocol.

The UBA were set up by Navy personnel in accordance with standard procedures. High Performance Sodasorb (4-8 mesh, W.R. Grace and Co., Atlanta, GA) was used as the CO_2 absorbent in the MK-15, pre-packed lithium hydroxide was used in the EX-19. Air was the diluent gas in both UBA, and oxygen partial pressures were maintained at 0.7 ATA ± 0.1 ATA.

Divers were submerged to 29 fsw (5 fsw below the chamber depth of 24 fsw) while breathing on a MK-15 UBA mouthpiece. The UBAs were suspended in an adjustable rack as if being worn by a diver swimming in a prone position (Fig. 1). The diver mounted a specially modified waterproofed Collins bicycle ergometer (Collins, Inc., Braintree, MA) just in front of the UBA. The rack was then adjusted by a tender to place the bottom of the UBA even with a point either 7 cm above the suprasternal notch (SN-7), 3 cm below (SN+3) or 13 cm below (SN+13) the suprasternal notch. (In practice, the 7th cervical vertebrae (C7) was used as a convenient anatomical reference, and the dorsal surface of the UBA shell was placed opposite C7, as well as 10 or 20 cm below C7. In keeping with convention, however, all measurements in this report are referenced to the SN.)

The above values for UBA placement generated hydrostatic loads that allowed testing of the Middleton and Thalmann goals (1981). Loads were both more negative and more positive than recommended in the specifications. The most positive hydrostatic pressure (SN+13) corresponded to that at the mean location of the lung centroid in upright, immersed divers (Taylor and Morrison, 1989).

Studies were performed in the wet pot of the MRCC from 0900 to 1600 h with a 1-hour break for lunch. Water temperature was thermoneutral for exercising divers (28 ± 1 °C). Typically, two divers at a time rode the bicycle ergometers. Four divers could thus experience all three hydrostatic loads on a given day. On the second day of the dive the divers experienced the same loads but in a different order from the previous day. The loads were presented to the divers in no particular order.

The exercise protocol consisted of a 5-min warm-up at 50 W, followed by 25 min at 1.5 W/kg (moderately heavy work). The work rate was set on the electronic ergometer. If divers complained of knee pain the workload was reduced to a minimum of 100 W. The divers' average weight was 82.3 ± 9.9 kg (mean ± SD), and the mean work load provided by the ergometer was 118 ± 4 W. Since the divers were in water, they performed approximately 25 watts of additional hydrodynamic work not accounted for by the ergometer (Thalmann et al., 1979). Therefore, the actual mean workrate was approximately 140 watts.

Oxygen consumption (a measure of global energy cost) was estimated from the decline in O_2 bottle pressure using the following equation:

$$\dot{V}O_2 = \left[\left(\frac{\Delta P}{\Delta T} \right) \cdot \left(\frac{Vb}{14.7} \right) \cdot \frac{(273)}{(T+273)} \right] \quad (1)$$

where $\dot{V}O_2$ = O_2 consumption (l/min STPD), $\Delta P/\Delta T$ is the rate of change of O_2 bottle pressure (psi/min), Vb = O_2 bottle volume in liters, 14.7 = psi/ata conversion, T = O_2 bottle temperature (°C). This technique was originally described by Jaggears and Thalmann (1983) in a study of the MK-15 UBA. The ergometer work rate was chosen to yield a steady state oxygen consumption of 2 l/min or above.

Mouthpiece pressure and pressures in the O_2 bottle of the MK-15 were measured by Validyne differential pressure transducers (Validyne Engineering, Northridge, CA). All pressures were recorded continuously on a Nicolet digital oscilloscope (Model 4094A, Nicolet Scientific, Princeton). Heart rate was measured from a waterproofed 3-lead ECG and monitored on either a Spacelabs (Model 90602, Spacelabs, Redmond, WA) or Hewlett-Packard (Model 26005; Hewlett-Packard, Palo Alto, CA) monitor.

A breathlessness or dyspnea score, taken every 5 minutes during the study, was based on a 5 point category scale as follows:

0 - no unusual symptoms

1 - breathlessness noticeable, does not affect comfort or performance

2 - breathlessness moderate, general discomfort

3 - severe breathlessness, work limiting

4 - early work termination - given by investigator only

This is an ad hoc category ratio scale similar to one used by NEDU during testing of the EX-19 (Knafelc, 1988). A hydrophone was used to communicate instructions to the diver, but the diver's communications were limited to hand signals monitored by a video camera. Following each session the divers were questioned about their sensations during the exercise.

Statistics

Since dyspnea score was a ranked variable, the non-parametric Spearman rank correlation was used to correlate dyspnea score with bag placement. A P-value of 0.05 or less was required for significance of the correlation.

RESULTS

Breathing Resistance Effects (DP)

Mouth pressures measured from peak inspiration to peak expiration (DP) result from breathing resistances created by hoses and CO_2 canisters. Since large resistances and DPs can induce breathlessness in exercising divers, we must consider their potential influence in this study.

We first compared the mouth pressures and gas densities found in this study with conditions found in a large series of dives at NEDU. From the NEDU data Clarke et al. (1989) determined regression equations relating dive outcome with the gas density and mean mouth pressure occurring in each NEDU dive. In general, the lower the density, the higher the pressure tolerated by the NEDU divers.

In the current series of dives to 29 fsw, gas density in the divers' airways was 2.2 g/l (assuming 37 °C, saturated gas). Based on the regressions found in Clarke et al. (1989), DP would have to exceed 42 cm H_2O before there would be significant risk of respiratory limitation. DP did not exceed 28.5 cm H_2O; therefore, we conclude that there was virtually no chance of a diver failing to complete exercise due to UBA breathing resistance alone.

Nevertheless, the deleterious effects of even moderate resistances could influence a diver's response to hydrostatic loads if the resistance was unevenly distributed across the loads. We examined that possibility. Due to occasional flooding of the pressure sensing line, complete data sets were only obtained in 6 of the 13 divers, however, for those dives there was no significant variation in DP across the load. The mean DP was 14 ± 4, 15 ± 5, and 11 ± 2 cm H_2O (mean ± SD) for SN-7, SN+3, and SN+13, respectively. Since DP did not vary across the hydrostatic loads, it could not have biased the divers' perceptions of the loads. As further evidence of this, the divers' perception of breathlessness did not distinguish between high and low DPs. DP's both above and below 20 cm H_2O were equally distributed between dyspnea scores of 0 and 1. We thus conclude that the breathing resistance of the UBA's had a negligible influence on our findings.

Oxygen Consumption

Oxygen consumption measurements were consistent with no variation across the hydrostatic loads.

Table 1. Oxygen consumption vs. hydrostatic load

LOAD	n	$\dot{V}O_2$ (l/min)
SN-7	28	2.02 ± 0.55
SN+3	27	1.99 ± 0.40
SN+13	30	1.99 ± 0.59

This $\dot{V}O_2$ equates to between 50-60% of the expected maximum oxygen consumption for young, healthy males.

Hydrostatic Loading

The objective of this study was to determine the optimal hydrostatic load for closed-circuit UBA, using the MK-15 as a model. Contrary to expectations, no UBA position had universal appeal. Diver preferences ranged across the entire hydrostatic loading scale, and dyspnea scores were not related in any consistent manner with breathing bag placement (Table 2). Very few reports of discomfort (dyspnea score 2 or higher) were elicited by this protocol. One diver was not discriminatory; he gave a rating of 2 for all loads. Only four other divers gave ratings of 2 or more. Of those four, three objected to the most positive pressure, one to the most negative pressure. The Spearman correlation coefficient relating dyspnea score to static load was only -0.026, with a non-significant P level of 0.80.

Table 2. Dyspnea score vs. hydrostatic load

	Dyspnea Score				
	0	1	2	3	4
SN-7	16	17	2	0	0
SN+3	12	13	1	0	0
SN+13	17	11	3	1	0

Various reasons were given by the divers for preferring one load over another. One diver, who consistently preferred positive pressure, commented that he liked the assistance to inspiration provided by positive loads, and disliked the work of inhaling against negative loads. Another diver, who preferred negative pressures, objected to the feeling of over-inflation experienced during positive loading. The majority of divers preferred the intermediate pressure, which corresponded roughly to that at the suprasternal notch when the diver was erect.

EX-19/MK-15 Comparison

The EX-19 prototype AUBA was successfully used for 8 runs. Unlike the MK-15, the EX-19 was worn on the divers' backs for this comparison. Divers who used both UBAs returned dyspnea scores of either 0 or 1 for both UBA. Diver comments regarding the EX-19 were, with one exception, highly favorable. The only stated preference for the MK-15 over the EX-19 was probably influenced by a non-UBA-related event; the diver described an uncomfortable heating by a warm-water discharge in the MRCC wetpot.

Four divers exercised with both the MK-15 and the EX-19. Table 3 lists their mean mouth pressures (in cm H_2O).

Table 3. Peak-to-peak pressure (DP) in four divers

	MK-15		EX-19
Diver	Load	DP	DP
1	SN-7	22.3 ± 1.5	17.6 ± 1.0
	SN+13	9.8 ± 0.5	-----
2	SN+3	14.9 ± 1.4	20.2 ± 1.9
	SN+13	11.2 ± 0.6	-----
3	SN+3	10.8 ± 1.6	14.9 ± 0.8
		-----	17.8 ± 1.2
4	SN+3	10.6 ± 0.6	16.7 ± 0.9
		-----	15.7 ± 1.5

Figure 2 shows the mean pressure developed by each of the above divers with both UBA. On the average, the mean DP with the EX-19 was 42% greater than with the MK-15. In spite of this, the divers expressed an overall preference for the EX-19.

Differences between the inhalation and exhalation resistances of the two UBAs could conceivably have accounted for the subjective preferences of the divers. However, the ratio of expiratory to inspiratory pressures in both UBA were essentially identical (Table 4). All the MK-15 data in Table 4 was obtained with the most comfortable hydrostatic load (SN+3).

Table 4. The proportioning of breathing resistance

	MK-15			EX-19		
Diver	Insp	Exp	Ratio	Insp	Exp	Ratio
1 Mean	7.5*	15.8	2.1	4.9	12.1	2.5
SD	±1.2	±1.8	---	±0.8	±0.7	---
2 Mean	2.6	6.1	2.3	4.1	11.2	2.7
SD	±0	±0.5	---	±0.5	±0.9	---
3 Mean	2.8	7.8	2.8	---	---	---
SD	±0.4	±0.5	---	---	---	---
4 Mean	---	---	---	6.4	12.9	2.0
SD	---	---	---	±1.7	±0.9	---
AVG	**4.3**	**9.9**	**2.3**	**5.1**	**12.1**	**2.4**

*mouth pressure in cm H_2O

Negative Pressures

Our quantitative data suggests that the most negative hydrostatic load used in our study (SN-7; 7 cm H_2O more negative than the current standards allow) was tolerated as well as the other loads.

This suggests that if the loading in the S-TRON prototype EX-19 had been as much as 7 cm H_2O more negative than the specifications, it might still have been reasonably well-tolerated. However, the reported negative loads of 15 and 22 cm H_2O (Knafelc, 1988) were apparently just too far from the specifications to be acceptable.

DISCUSSION

Diver Position

Although the MK-15 UBAs were arranged in a prone position to minimize the effects of UBA elastance (Joye et al., 1989a), the divers exercised in an upright position. One justification for the upright posture is that divers may frequently be transported to their dive site while upright. This position is therefore operationally relevant.

However, the upright posture also served another purpose. The upright posture results in less comfortable work than does the prone position (Carlson, 1987; Hashimoto, 1984), and accentuates the effects of negative hydrostatic loads (Derion, 1988). Thus, that position should have increased our divers' sensitivity to hydrostatic loading and applied a conservative bias to our results.

Optimal Hydrostatic Loads

Others have shown that hydrostatic loads equivalent to +10 to +20 cm H_2O relative to the SN improve diver comfort and work capacity during upright immersion (Carlson et al., 1989; Taylor, 1987). However, as previously reported (Jarrett, 1965; Thompson and McCally, 1967), the elimination of transpharyngeal pressure gradients are important for the tolerance of those positive pressures. The use of helmets (Carlson et al., 1989), or of full face masks with facial counter-pressure (Taylor, 1987), accomplish this, but were not used in our study. Not surprisingly then, most divers complained of jaw fatigue and puffing of the cheeks when pressures more positive than SN+3 were used.

There was no objective evidence indicating which of our three loads were physiologically preferable. Dyspnea scores showed no differences among the loads. We base our conclusions, therefore, on the subjective impressions of the divers, specifically on their after-exercise evaluations.

From the divers' comments we conclude that when a closed-circuit UBA is to be used with a mouthpiece only, hydrostatic loading in an erect position should be equal to or slightly more positive than pressure at the suprasternal notch. Based on the literature, higher pressures may be of benefit during heavy exercise, where a diver can most profit from inspiratory assistance. Pressures greater than 20 cm H_2O would be best tolerated, however, with the use of a helmet or a pressure-compensated band mask.

EX-19 vs MK-15

Although our divers had a limited exposure to the NCSC EX-19, their overall impression was highly favorable. What requires some explanation, however, is why DP was often higher in the EX-19 than the MK-15 (Fig. 2), and how that could correlate with a favorable diver impression.

We can discount differences in the distribution of inspiratory and expiratory pressures (Table 4). That leaves two alternative explanations. One is that divers are only sensitive to resistance (the quotient of pressure and flow) and not pressure per se. While DP was higher in the EX-19 than in the MK-15, the resistance of the EX-19 was presumably as low or lower than in the older UBA. Since neither flow nor resistance ' as measured in this study, we cannot assess the reasonableness of that hypothesis.

Peak-to-peak mouth pressure is affected by both UBA resistance (R) and elastance (E).

$$DP = (E \cdot V) + (R \cdot \dot{V}) \qquad (2)$$

$\dot{V}$ represents flow, the first derivative of volume (V). While the MK-15 was oriented to minimize elastance, the EX-19 was in a position that maximized that elastance. Elastic pressure is generated by vertical motion of the air - water interface in breathing bags (Joye et al., 1989a), so a vertical orientation of breathing bags on the chest (as in the NCSC prototype) should exaggerate elastance. Indeed, unmanned tests of the NCSC EX-19 at NEDU showed a pressure-volume (P-V) loop that had a greater slope (elastance) than did the S-TRON EX-19 (Knafelc, 1988).

We have recently described ways for measuring elastance in UBA (Joye et al., 1989b), but much has yet to be learned about the physiological effects of UBA elastance. Our understanding of the MK-15/EX-19 comparison must await the outcome of ongoing research on elastic loading.

CONCLUSIONS

1. Divers usually stated a preference for hydrostatic loads lying within the range of current hydrostatic loading limits (0 to +10 cm H_2O relative to the SN).
2. Divers occasionally stated a strong preference for more negative or more positive pressures than allowed in the specifications. If possible, breathing bag design should allow adjustments of hydrostatic loading by individual divers. This could be best accomplished by divers altering the volume of gas within their breathing bags. The most versatile arrangement allowing such load variation would have large breathing bags lying over the shoulders and down the chest. This bag design was found in the NCSC prototype, but not the S-TRON prototype.
3. Hydrostatic loads as much as 7 cm H_2O more negative than the current standards do not limit the ability of divers to perform moderate exercise at shallow depths.
4. Static loads equal to the so-called lung centroid pressure (SN+13) frequently caused uncomfortable feelings of over-inflation when applied through a mouthpiece. Although pressures higher than SN+10 may improve the exercise tolerance of divers, this pressure should be applied by helmets, thus eliminating upper airway over-inflation.
5. Procedures for measuring elastic loading should be incorporated into UBA testing procedures at NEDU to insure that hydrostatic and resistance measurements are not being confounded by an appreciable but unknown UBA elastance.

REFERENCES

Carlson, N.A., J.R. Clarke, and E.T. Flynn. Effects of immersion and static lung loading on ventilatory work and endurance. In review.

Clarke, J.R., S. Survanshi, E. Thalmann, and E.T. Flynn. Limits for mouth pressure in underwater in breathing apparatus (UBA). In: Lundgren and Warkander (eds.). Physiological and Human Engineering Aspects of Underwater Breathing Apparatus. Undersea and Hyperbaric Medical Society, Inc., Bethesda, MD, 1989.

Derion, T. Ventilatory response to posture and static lung loading during underwater exercise. Doctoral dissertation. University of Wisconsin, Madison, 1988.

Flynn, E.T., E.M. Camporesi, and S.A. Nunnelly. Cardiopulmonary responses to pressure breathing during immersion in water. In: Lanphier, E.H. and Rahn, H. (eds.). Man, Water, Pressure. Vol. II. State University of New York, Buffalo, NY, pp. 79-94, 1975.

Hamilton, J.D.M. Conventional Diving System (CDS), EX-19; Interim Report of Testing. NEDU Unit, 22 Mar 1988.

Hashimoto, A. Effects of posture and water immersion on diaphragmatic function. Doctoral dissertation, University of Wisconsin, 1984.

Jaggears, F.R., and E.D. Thalmann. Manned evaluation of MK-15 closed-circuit UBA canister duration at 13.4 °C and 2 °C. Navy Experimental Diving Unit Report No. 6-83, 1983.

Jarrett, A.S., Effect of immersion on intrapulmonary pressure. Journal of Applied Physiology, Vol. 20, pp. 1261-1266, 1965.

Joye, D.D., J.R. Clarke, N.A. Carlson, and E.T. Flynn. Formal descriptions of elastic loads encountered in the use of underwater breathing systems. In: Lundgren and Warkander (eds.). Physiological and Human Engineering Aspects of Underwater Breathing Apparatus. Undersea and Hyperbaric Medical Society, Inc. Bethesda, Md. 1989a.

Joye, D.D., J.R. Clarke, N. Carlson, and E.T. Flynn. Formulation of elastic loading parameters for studies of closed-circuit Underwater Breathing Systems. Naval Medical Research Institute Technical Report No. 89-89, 1989b.

Knafelc, M.E. Unmanned and manned evaluation of a prototype closed-circuit underwater breathing apparatus, the EX-19. Naval Experimental Diving Unit Report No. 5-88, 1988.

Middleton JR, Thalmann ED. Standardized NEDU unmanned test procedures and performance goals. Naval Experimental Diving Unit Report No. 3-81, 1981.

Taylor, N.A.S., and J.B. Morrison. Lung centroid pressure in immersed man. Undersea Biomedical Research, Vol. 16, pp. 3-19, 1989.

Taylor, N.A.S. Effect of breathing gas pressure on respiratory mechanics of immersed man. Doctoral Dissertation, Simon Fraser University, 1987.

Thalmann, E.D. Effects of immersion and static lung loading on submerged exercise at depth. Undersea Biomedical Research, Vol. 6, pp. 259-290, 1979.

Thompson, L.J., and M. McCally. Role of transpharyngeal pressure gradients in determining intrapulmonary pressure during immersion. Aerospace Medicine, Vol. 38, pp. 931-935, 1967.

FIGURE LEGENDS

Figure 1: Orientation of the MK-15 UBA relative to the exercising diver. This unusual orientation was designed to minimize the confounding influence of UBA elastance. The rack on which the UBA rested was adjusted vertically to correspond to one of several hydrostatic loadings. Those loads were 7 cm H_2O more negative than (7 cm above) the suprasternal notch (SN-7), 3 cm H_2O more positive than (3 cm below) the suprasternal notch, and 13 cm H_2O more positive than the SN.

Figure 2: Comparison of mean peak-to-peak mouth pressure in four divers who exercised with the MK-15 UBA (in a horizontal position) and the NCSC prototype EX-19 (in the vertical position).

FIGURE 1

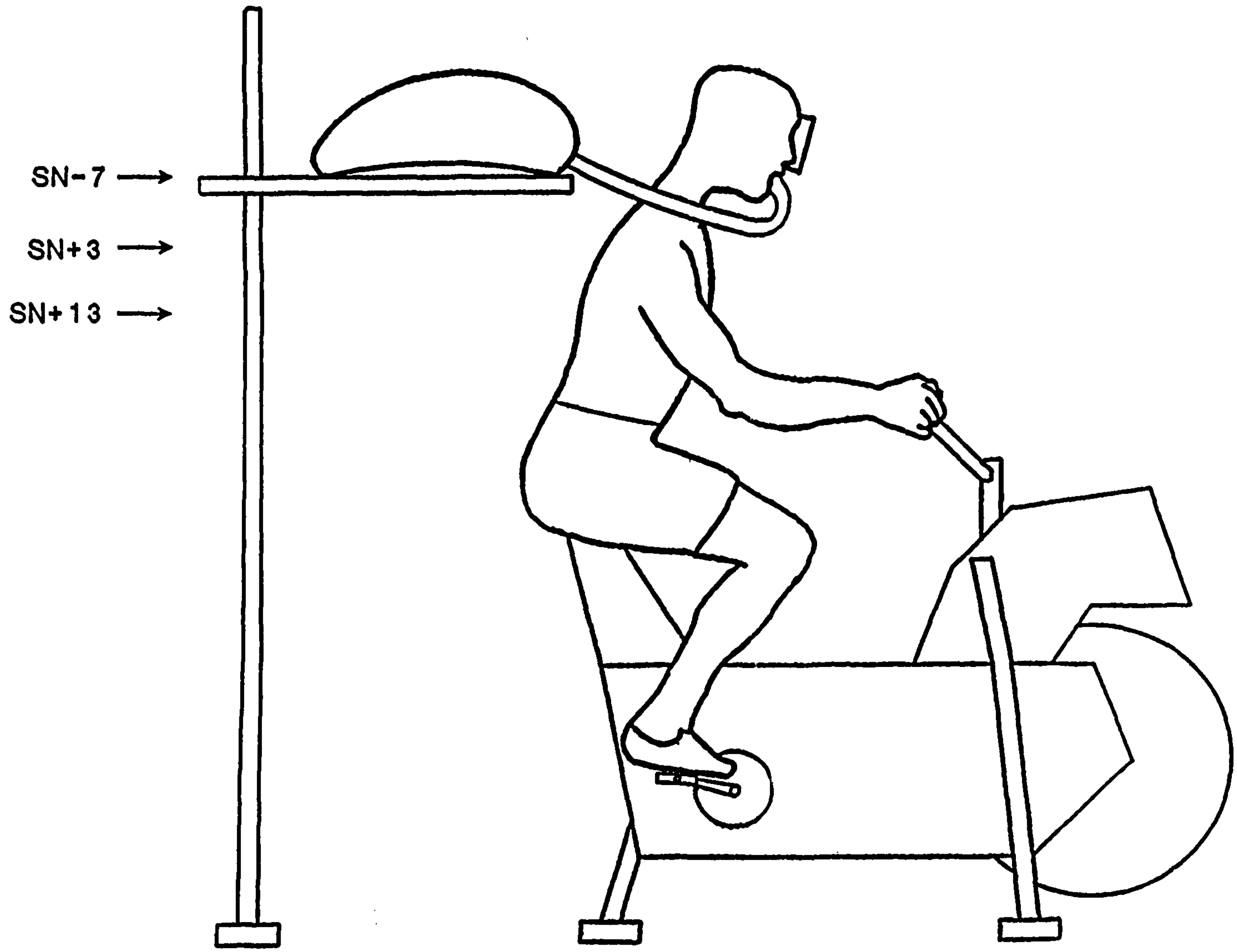

FIGURE 2