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HUMAN ENGINEERING CONSIDERATIONS IN THE EVALUATION OF DIVING EQUIPMENT

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Abstract

Highlights are presented of a particular human factors approach to one aspect of diver performance – the assessment of diving equipment, its impact on the diver's work, and to a degree, his physiological state. Briefly reported are a range-of-motion biomechanical analysis of the flexibility of the two systems and a heart rate-work correlation comparison of the two systems.

INTRODUCTION

The measurement of an individual's performance and the interaction with his environment proceeds with minimal difficulty under normal working conditions, that is, a relatively well-lighted work situation, normal air with a temperature within the comfort zone, and unrestricted movements. Difficulties in measurement increase enormously, however, when the assessment of performance is transferred to the degraded conditions of the undersea environment with its accompanying turbidity, cold, potential marine hazards, and interfering current. Add to this a diver who is under the abnormal physiological conditions of pressure, breathing an exotic gas, and finally, of necessity, wearing protective equipment that limits his mobility while offering him protection against the hostile environment. "A man in armour is his armour's slave," wrote Robert Browning in Herakles; protection always buys a certain amount of immobility, and it has its impact on the performance of a diver.

In the brief compass of this paper, we will cover highlights of a particular human factors approach to the assessment of one aspect of diver performance — the assessment of diving equipments, its impact on the diver's work and, to a degree, his physiological state.

HUMAN FACTORS IN ENGINEERING DESIGN

Three major variables in the design of underwater equipment have been (1) the engineering of apparatus capable of performing safely and effectively under extreme environmental conditions; (2) the physiological assessment of diver operations with particular emphasis on such problems as decompression and respiratory physiology; and (3) the human engineering of diver equipment so that diver performance can be optimized for efficiency, safety, and comfort. The last of these is considered essential in the

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Military Standards 1472 (DOD 1972), which provides human engineering requirements for military systems, equipment, and facilities.

In designing equipment for the diver these considerations have frequently been waived as less critical to the overall design. Indeed, there has been little systematic human engineering of diving equipment accomplished. Where hardware considerations are paramount, all too often the diver is implicitly or explicitly expected to compensate for possible shortcomings in gear. This situation is not unique to the diving community. For example, thrust-weight relationships in space missions could override human factors: weight savings in antisubmarine warfare achieved by removing the toilet facility in the P-3B presumably took precedence over crew comfort. An aeronautical engineer weighing fuel consumption might provide a hard figure: "Give me 700 pounds less structural weight and I'll give you 40 minutes more mission time." A human factors engineer could probably provide only anecdotal information about crew reluctance to use a plastic bucket instead of a toilet, which led to crews later boasting about a "14-hour bladder." This very pride in adversity, or what we would like to call "perversity in adversity," is often found in high-risk occupations whose practitioners find a certain amount of pride in overcoming adverse conditions. Certainly this is true of many divers — but – it is our position that human engineering considerations are crucial for maximal safety and efficiency, and the success of such operations.

As examples of human engineering considerations in the assessment of diving equipment, we will report briefly on two phases of an intensive technical evaluation of the U.S. Navy prototype Mark XII diving system (Fig. 1) under the direction of LT Donald Chandler of the U.S. Navy Experimental Diving Unit. Through the collaborative efforts of the Performance Physiology Laboratory, University of California at Los Angeles, and the Behavioral Sciences Department, Naval Medical Research Institute, two aspects of the overall human factors assessment were accomplished – those of biomechanical analysis and physiological monitoring of work (Bachrach, Egstrom, and Blackmun in press; Armstrong, Bachrach, Conda, Holiman, and Egstrom 1974).

Biomechanical analysis of diving dress. Properly to evaluate the Mark XII, it was elected to compare it with the standard Navy diving system, the Mark V (Fig. 2), since there might be a possibility of proposing a replacement of the Mark V by the new prototype Mark XII, or a modification thereof. The comparison with the Mark V was based on the concept that the technical evaluation would have to demonstrate that the replacement system was as good or better in standard usage than the former diving system.

One of the presumed advantages of the Mark XII was its greater flexibility over the Mark V diving dress. To assess this possible improvement in flexibility, we accomplished a series of 14 measurements based upon dynamic anthropometric measures (Hertzberg 1972). Static anthropometry is concerned with size and dimension as critical variables. It has just begun to be applied systematically in Navy operations (Beatty, Berghage, and Chandler 1971; Beatty and Berghage 1972). Dynamic anthropometry involves functional measurements concerned with the quantitative assessment of joint angle changes and range of motion while people are performing volitional movements. It is, in essence, a mechanical view of muscle action. The reference points we chose for biomechanical measurement were most appropriate to assess the flexibility of the system.

Hertzberg (1972) has suggested that the three most important body joints articulated by means of ligaments are hinged joints such as the fingers; pivot joints, such as the elbow; and ball and socket joints such as the shoulder and hip. Range of motion is limited by the entire joint body configuration, the attached muscles, ligaments, and tendons, as well as the amount of fat present in the individual. These are not constant, but vary from person to person, and indeed, within an individual from time to time.

Range-of-motion movements are limited by internal mechanical stops (for example, how far can a movement go and what is its limit?). To measure internal mechanical stops imposed by any configuration of the individual diver, one must first measure the diver in a swim suit to establish base lines. The supposition is that the diving equipment itself will impose external mechanical limitations that impede the normal, undressed range-of-motion of the diver. The presence and magnitude of such impedance is basic to biomechanical analysis.

Fourteen separate range-of-motion measurements were selected. These motions represented gross body movements used in hard-hat diving and were presumed to be the ones most likely affected by the diving suits (Fig. 3). The general types of movement measured were flexion (reducing the joint angle), extension (increasing the joint angle), abduction (movement away from the body midline), and rotation (turning or twisting). The joints measured were the shoulder, elbow, hip, knee, and trunk. Range of joint movement was measured with a compass. All measures were taken first in a swim suit, then dry and wet in a tank. Figs. 4 through 6 are examples of measuring techniques in both wet and dry modes.

After the movements had been measured in degrees, flexibility loss in each suit was calculated in relation to the swim suit base lines. The calculted impairment in degrees was converted into percentages; paired t tests were then performed to assess the flexibility differences between the two systems.

The results of combining wet and dry measurement data showed the Mark XII was equal to or superior to the Mark V in flexibility, with the Mark XII having greater flexibility in trunk extension; shoulder joint abduction, flexion, and horizontal flexion; knee flexion, and hip extension and abduction. In 6 of the 14 range-of-motion measurements in the wet mode the Mark XII was significantly more flexible than the Mark V. In 8 of the 14 measurements in the dry mode the Mark XII was significantly more flexible in the Mark V. Two important arm movements, shoulder joint abduction and shoulder joint flexion, were clearly superior in the Mark XII because it is difficult to raise the arm beyond a horizontal plane in the Mark V, which obviously makes overhead movements difficult.

Physiological aspects of work. Another phase of the diving systems evaluation used tool tasks to measure diver performance in approximately 60 ft of water off the YRST from the Harbor Clearance Unit off Barber's Point, Hawaii. The tasks used in the evaluation were the Enerpac, a cutting task described by Quirk (1974); a task developed around a self-contained load-handling pontoon (Conda and Armstrong 1973); and the UCLA pipe puzzle, an underwater assembly task (Weltman, Egstrom, Willis, and Cuccaro 1971). The results of the pipe puzzle evaluation are of particular relevance to our discussion.

The UCLA pipe puzzle is a pipe structure, standing about 7 ft high on a 4- x 5-ft base, fabricated from 2-in. galvanized pipe and correspondingly sized flanges, elbows, and valves. It also has an associated pressure test console containing a compressed gas supply. Two-man diver teams bolt the structure together from preassembled sections stored on the base, inserting gaskets and bolts as required. The resulting pipe work is pressurized and tested for leaks after the bolts have been adjusted to 30 foot-pounds of tension with a torque wrench. Various sections of the task weigh up to 50 lb.

The project requires a variety of underwater work skills including selection and fine manipulation of bolts, nuts, and washers, and the use of wrenches for torquing from various orientations and stabilizations. Manhandling and positioning the heavier parts requires knowledge and experience for efficient performance. Teamwork is a necessity for efficient completion and communication between divers and is requisite for certain task elements. Completion times, errors, and activity analysis can be evaluated along with heart rate, gas consumption, pre- and posttask cognitive measures, and the like.

Teams that are pretrained on the task will typically establish a stable performance after 3 to 5 rehearsals. The differences in completion times then can be attributed appropriately to the varied diving equipment, changed methodology, or specific environmental conditions.

The divers were required to perform the UCLA pipe puzzle on alternate dives wearing each diving system in both the air mode and HeO_2 mode. In both modes the divers were breathing air. The times to completion on the various phases were monitored through the use of a closed circuit video tape system and standard diver communications.

Fig. 7 shows the results of the time comparison. These data are drawn from the efforts of five pairs of Navy divers who performed the task first in a shallow tank (control), then four additional times at 60 ft in the open sea. The comparisons are interesting in that the Mark XII appears to provide for a similar level of performance in both the air mode and the HeO_2 mode. The Mark V, on the other hand, requires longer times to completion and shows a marked difference between the air and simulated HeO_2 mode. These differences appear to result from a higher degree of mobility while using the new modifications of diving equipment.

Another comparison of work on the UCLA pipe puzzle in both the Mark V and Mark XII diving dress was accomplished correlating work with heart rate measures taken in the water by an acoustic telemetry method developed by John Kanwisher (Kanwisher, Lawson, and Strauss 1974). Thus, the energy cost required by the diving dress could be inferred from heart rate-work correlations.

The practice of monitoring changes in heart rate to estimate the relative energy cost of work is based upon several assumptions. The first is that heart rate change and oxygen uptake have a parallel and linear relationship to progressively increasing work loads. The second assumption is that while diving bradycardia results in lower heart rates while underwater, it does follow the pattern of the first assumption.

The techniques used do not reveal precise differences, but they appear to provide generally useful information for comparisons of variables such as different equipment or methodology used by the same person while performing similar tasks.

An example of one diver's heart rate profile correlated with specific tasks is seen in Figs. 9 and 10. The diver had a resting heart rate on the deck of approximately 80 beats per minute. (Admittedly, resting heart rate is not as accurate as that taken with exercise, but it is nonetheless an efficient base line.) The same diver's performance in the Mark XII was significantly less strained than in the Mark V, with the highest peak at 168 beats per minute, suggesting that in this particular diver the stress of work in the Mark V was higher than that in the Mark XII.

The orchestration of physiological data and specific work tasks appears to be a crucial and valuable means of monitoring diver performance.

DISCUSSION

During this comparative study the same work methodology was utilized for all variations of the equipment. The divers were heavily weighted and worked with conventional tools. One is tempted to speculate upon the results of the comparison if the divers had adopted a revised work methodology based upon the flexibility and potentially lighter weight of the modified system. The present results reflect differences apparently due to the equipment limitations while utilizing similar work methods.

Part of the difficulty in this type of comparison is related to the inability to fix the precise cause of any decrements upon a single intervening variable such as equipment. The mechanical limitations of the equipment had been measured previously by techniques that involved range-of-motion comparisons for joint movements typically used by working divers. Such restrictions to movement are relatively straightforward and can be inventoried. Less straightforward, however, are differences due to the limitations imposed by individual diver strength and endurance. For example, in comparing flexibility between two sets of equipment (e.g., Mark V and Mark XII), a diver in one set of equipment might be required to work harder to overcome the equipment restrictions even though the flexibility of both sets might be similar. The effort required to achieve the flexibility could be substantially different due to differences in diver strength and endurance. Thus, such comparisons should include the monitoring of physiologic parameters such as heart rate, which is essentially linear with increased oxygen consumption and work load. Unfortunately, this very valuable comparative tool has not been used sufficiently to become a well-accepted basic measurement. Heart-rate data can be recorded by hard wire or telemetry methods, yet use of such methods has been limited to relatively few studies.

Another important variable involves the specific work methodology to accomplish the task. It is, indeed, interesting that one can become proficient and effective in completing a task even though he may be utilizing a relatively inefficient methodology. These problems are often the result of a lack of insight or experience with the problem at hand. Many of these inefficiencies are self-perpetuating due to the development of a technique that becomes described as "the way." Improvements upon the technique usually proceed slowly due to a failure to analyze the problem at hand in terms of its specific requirements. Underwater work requires a high degree of specific adaptation to the demands of the job, the environment, the equipment, and the diver. Generalizations on methodology should be evaluated carefully.

Any evaluation program requiring the observance of human behavior is also subject to variability of performance as a function of the psychologic status of the individual. The ability to work in a relaxed, controlled frame of mind is frequently hampered by stresses that are induced by such things as unfamiliarity with the equipment, job environmental variables such as cold or depth, and changes resulting from increased work loadings. These variables are exceedingly difficult (if at all possible) to measure, yet their influence upon performance is of major significance.

Performance decrements attendant to the addition of relatively mild stressors can easily account for 20 to 30% loss in effectiveness during underwater work. Experience and training for the specifics of the job appear to be the most realistic preventive measure currently available.

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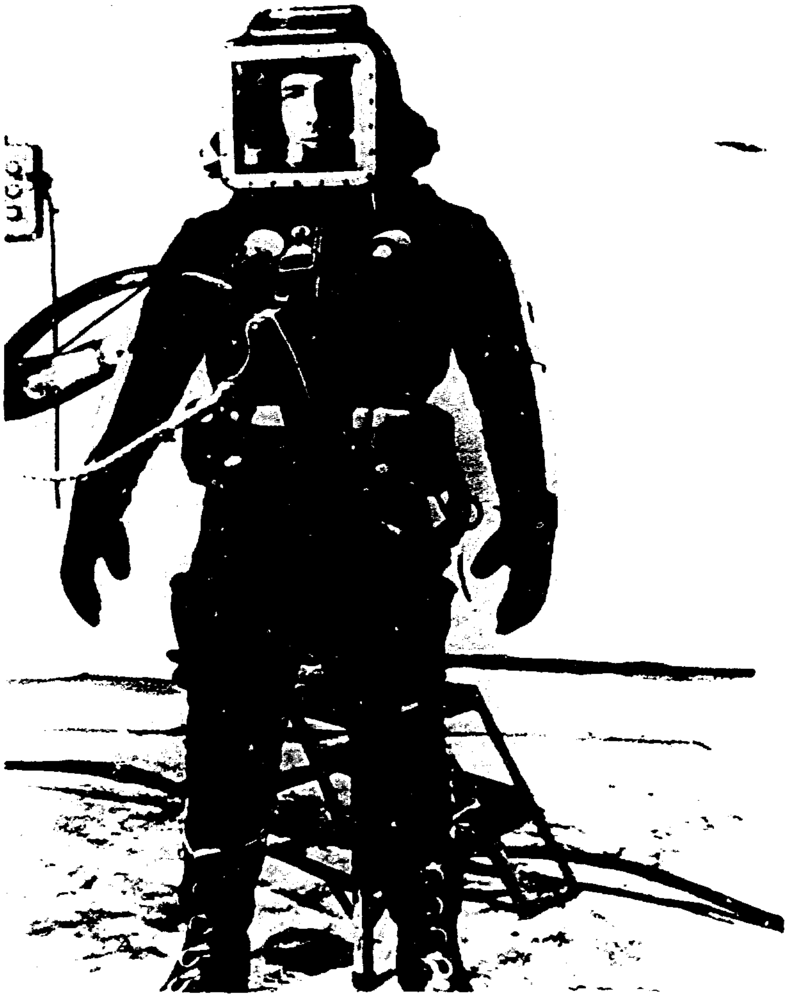
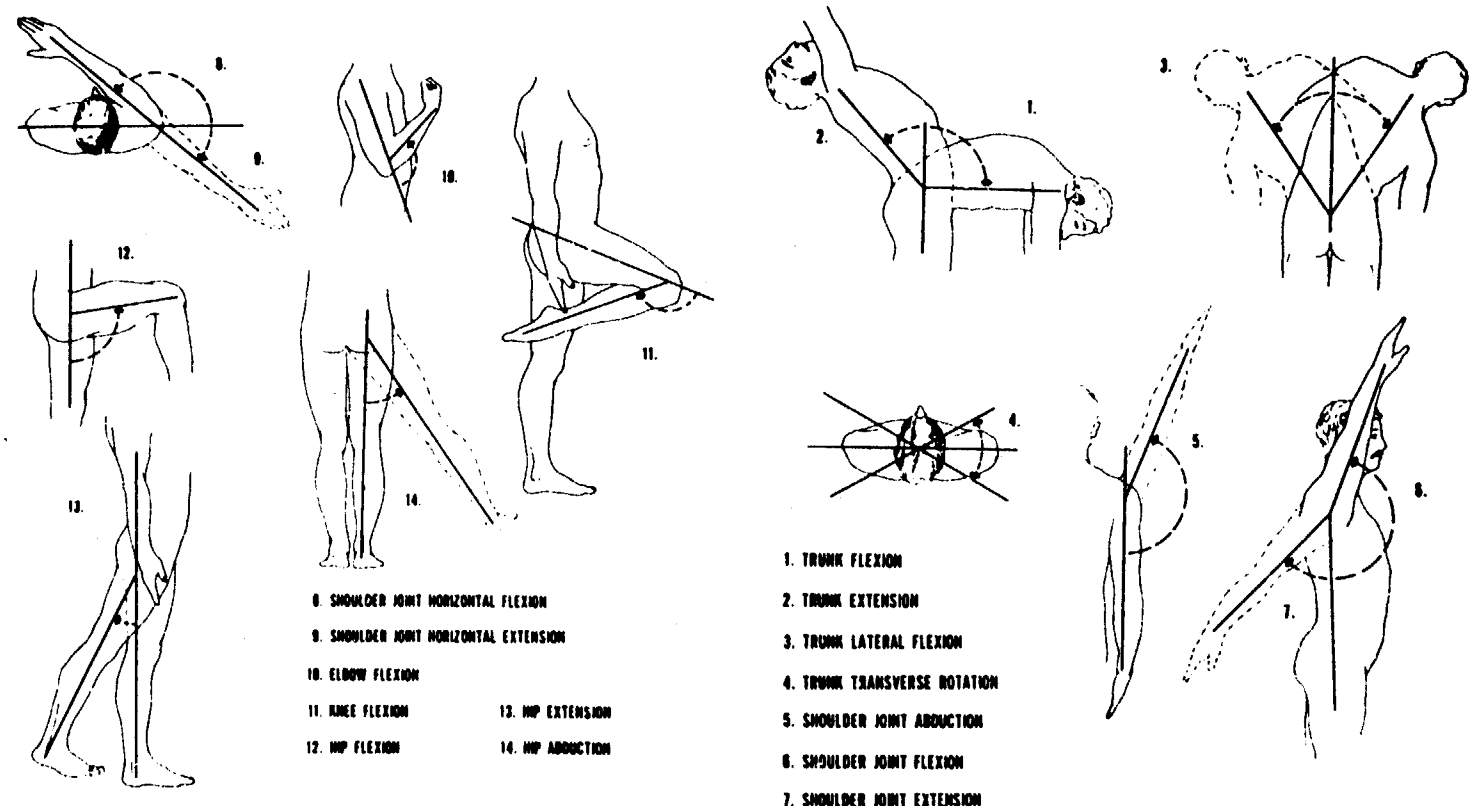


U.S. NAVY MARK XII PROTOTYPE SURFACE-SUPPORTED HARDHAT DIVING SYSTEM.

U.S. NAVY MARK V SURFACE-SUPPORTED HARDHAT DIVING SYSTEM.



Courtesy Bachrach, Egstrom, and Blackmun, in press; also Human Factors Society.

Fig. 3. Diagrams of the 14 anthropometric measurements.

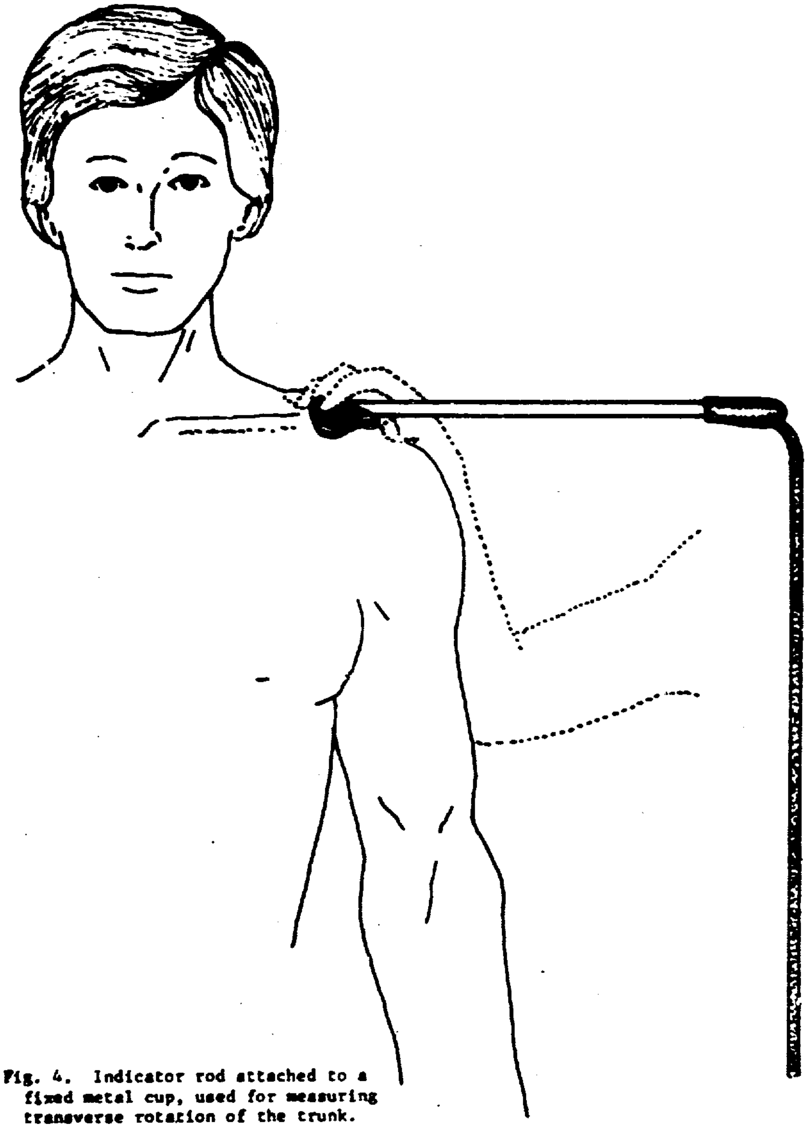
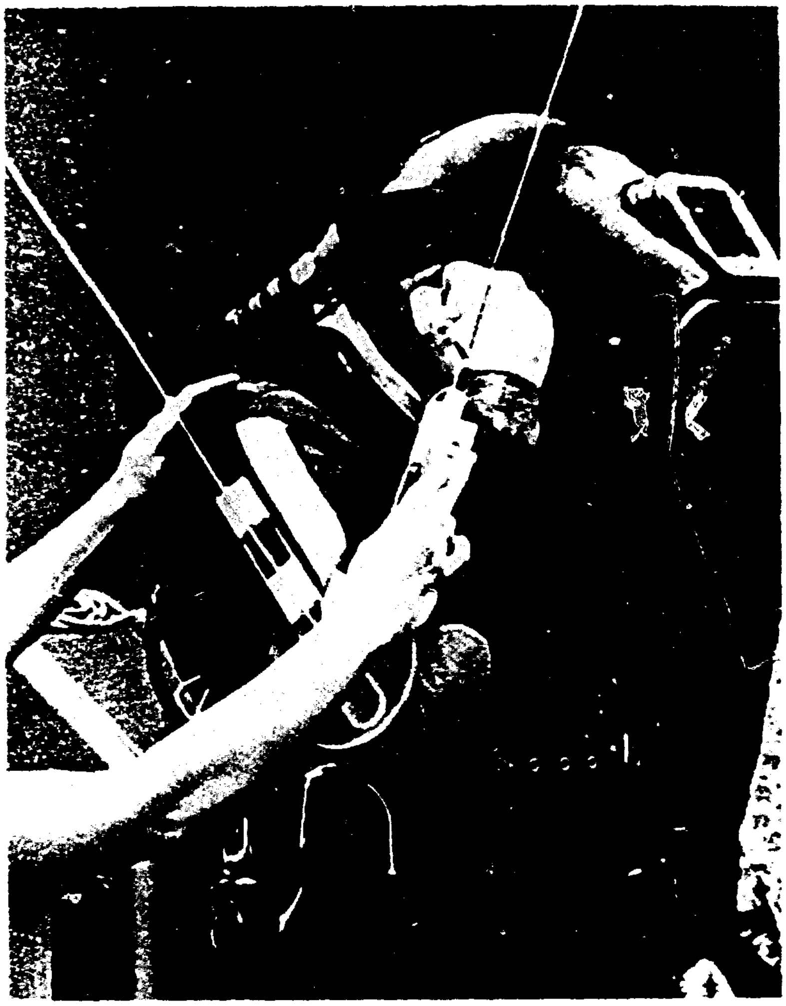


Fig. 4. Indicator rod attached to a fixed metal cup, used for measuring transverse rotation of the trunk.



MEASUREMENT OF ELBOW FLEXION IN THE MARK XII, DRY MODE.

MEASUREMENT OF KNEE FLEXION IN THE MARK V, WET MODE.

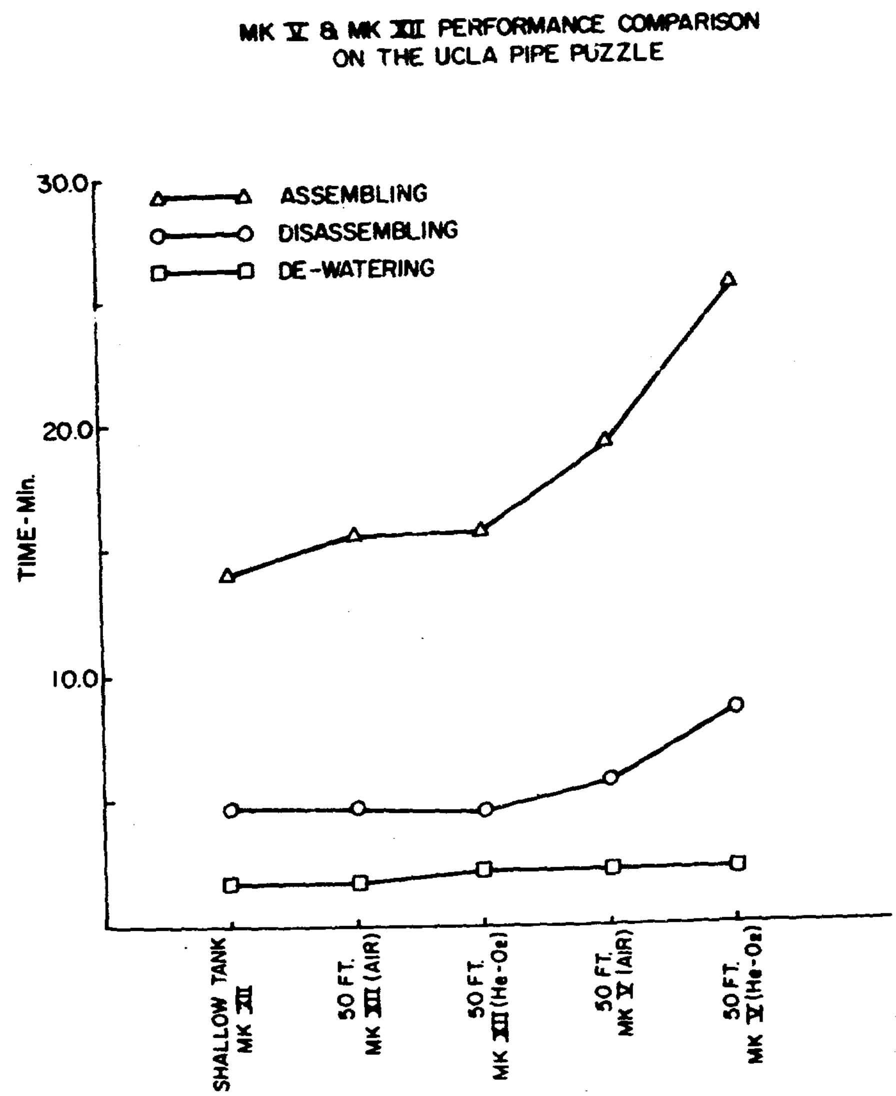


Fig. 7. Performance comparisons on the UCLA pipe puzzle in both systems. Breathing medium: AIR, on all modes.

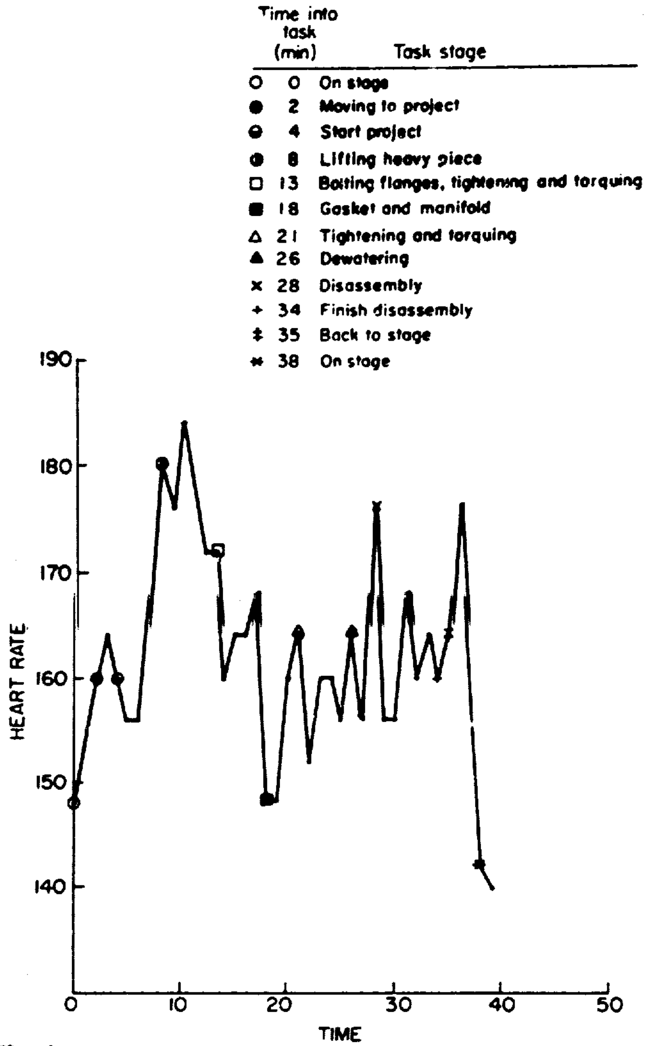


Fig. 8. Heart rate recordings for: Subj #1 - Pipe puzzle MKV-HeO_2 Mode breathing air

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13. ABSTRACT

Highlights are presented of a particular human factors approach to one aspect of diver performance - the assessment of diving equipment, its impact on the diver's work, and to a degree, his physiological state. Briefly reported are a range-of-motion biomechanical analysis of the flexibility of the two systems and a heart rate-work correlation comparison of the two systems.

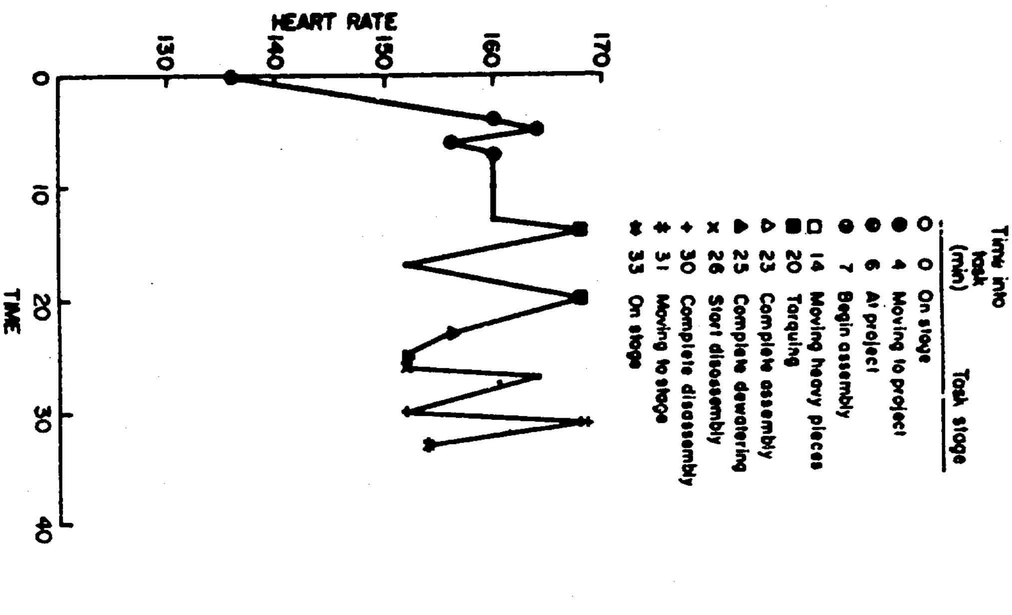

Fig. 9. Heart rate recordings for: Subj. #1 - Pipe puzzle Mk XIII, HeO_2 Mode breathing air

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10

QUESTIONS AND ANSWERS

Q. What can we anticipate in the use of diver monitoring equipment as a standard practice for on-the-spot evaluation of working divers?

A. I believe that diver physiological monitoring is going to be a standard practice. I think it is one of the most important bits of information we have about diver performance as well as impending problems of disfunction. I think it will become standard, particularly, as the equipment becomes less bulky, more miniaturized, and more effective.

Q. Which physiological variables would it be best to monitor?

A. Well, optimally, if you could get O_2 consumption, CO_2 heart rate, and respiration, these would be ideal. Given one alone, I would opt for heart rate.

Q. If you depend on a monitor, to what extent do you feel you will have false indications as far as making judgments as to what the diver's physical condition is?

A. Well, I think this is an interesting question, because it depends on what you really mean by false information. I think that the divemaster right now is required to make judgments on the diver's performance on less than adequate information. Certainly, we have no work tolerance tables; we have no real physiological indices. For example, if I may mention still another physiological monitoring, Peter Bennett and I were doing tremor measurements on the 1000-foot dive at Duke last January, as we have done on most of these dives; at 870 feet, the storage level, we had three divers in the chamber and we did the forced transducer trimmer measurement which has been developed for quantitative measure tremor. We've got a pathological tremor of 870 feet just before they were going to compress to 1000 feet. They were resting at 870 ready to travel to 1000 feet and at 870 two of the three divers have 3 to 5 Heartz tremor, which is in the pathological range; it disappeared as they were compressed to 1000 feet, so we felt it wasn't a pressure phenomenon or a gas phenomenon; we felt, then, it must have been – for want of a better word which we were reluctant to use – "apprehension". Now, this is not false information. We did get the pathological information, we do get high peaks in divers on heart rate. I think, then, that the divemaster has to decide how to use this information. I would not say abort the dive because you get a particular heart rate unless you sustain it for a while, but false information, no; I think the information is then to be subjected to judgment.

Q. How effective are current equipments? – equipment designs, such as diving systems?

A. I think that there has been very little human engineering done on diving equipment. I think that we are asked to dive to compensate; I think that there's a real need to go into such elements as visibility, which as Don Chandler mentioned and Joan Kinney has done for the Mark 12; I think that the human factors have been ignored to a large degree in diving equipment design. I'm not very pleased with the cumbersome kinds of equipment that are available to sports or commercial divers.

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