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**A Method of Evaluating  
Efficiency During Space-  
Suited Work in a Neutral  
Buoyancy Environment**

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## ABSTRACT

The purpose of this study was to investigate efficiency as related to the work transmission and the metabolic cost of various extravehicular activity (EVA) tasks during simulated microgravity (whole body water immersion) using three space suits. Two new prototype space station suits, the AX-5 and MKIII, are pressurized at 57.2 kPa (8.3 psi) and were tested concurrently with the operationally used 29.6 kPa (4.3 psi) shuttle suit. Subjects were four male astronauts who were asked to perform a fatigue trial on four upper-extremity exercises during which metabolic rate and work output were measured and efficiency was calculated in each of the suits. The activities were selected to simulate actual EVA tasks. The test article was an underwater dynamometry system to which the astronauts were secured by foot restraints. All metabolic data was acquired, calculated, and stored using a computerized indirect calorimetry system connected to the suit ventilation/gas supply control console. During the efficiency testing, steady-state metabolic rate could be evaluated as well as work transmitted to the dynamometer. Mechanical efficiency could then be calculated for each astronaut in each suit performing each movement.

## INTRODUCTION

Performing productive work in space has been a proven concept for over two decades. As early as Gemini GT-12 in November 1966, astronaut Edwin "Buzz" Aldrin established the capacity of man to work productively outside the protective spacecraft environment by performing EVA experiments and useful work for more than 5.5 hours (Mallan, 1971). Given the necessity of working in space and the high monetary cost of on-orbit time, optimizing performance and increasing efficiency are important tasks for future space flights. The current space shuttle suit has been successfully used to perform various EVAs ranging from satellite recovery to simulations of space station construction. While the shuttle suit maintains adequate joint flexibility and force transmission capabilities, the 29.6 kPa (4.3 psi) pressurization forces the astronaut to perform a 3.5 hour nitrogen washout or 100-percent oxygen prebreathing procedure prior to an "emergency" EVA to eliminate the risk of decompression sickness when depressurizing from the shuttle's earth-like 101.3 kPa (14.7 psi) ambient pressure (Horrigan, et al., 1989). Prebreathing is not only time-consuming and physically difficult to accomplish, but also decreases mission safety by hindering any attempt at an emergency or contingency EVA. The development of a space suit pressurized in the range of 55.2 to 69 kPa (7.8 to 9.7 psi) (decompression of ca. 12,000 feet from sea level) with comparable joint flexibility and low resistance to motion would not only eliminate the prebreathe period but would also optimize EVA performance (Horrigan, et al., 1989). The purpose of this study was to develop a method for evaluating the mechanical efficiency of space-suited work using three pressurized space suits during various EVA tasks under simulated microgravity conditions (whole body water immersion). Two new prototype space station suits, the AX-5 and MKIII, are pressurized at 57.2 kPa and were tested concurrently with the 29.6 kPa shuttle suit.

## METHODS

Four male astronauts were asked to perform a fatigue trial on each of four exercises during which metabolic rate and torque input was measured. The protocol (figure 1) was performed while suited, in foot restraints, and during whole body water immersion in the Johnson Space Center Weightless Environment Training Facility (WETF). The activities were selected to simulate actual EVA tasks and were performed in random order. Before any performed movements, the resting metabolic rate of each astronaut was established during the weigh-out period (the astronaut was held motionless and weighted to achieve

neutral buoyancy). During all testing phases, investigators, test directors, and suit technicians were in voice contact with each astronaut. Suit environmental control was managed and performed by space suit technicians.

To collect the torque transmission data, the test article consisted of an underwater dynamometry system to which the astronauts were secured by foot restraints. The dynamometer test apparatus consisted of an isokinetic dynamometer (Cybex II+) contained in a pressurized (N<sub>2</sub> charged) housing and mated to a height-adjustable stand with a gridded base platform. Repeatable placement of the astronauts and foot restraints was achieved by using the grid pattern on the base platform and the ruled height adjustments on the test stand. A stripchart recorder (Cybex) and an analog tape-recorder (TEAC) at the surface were used to collect and store data. Peak and mean torque values attained at a constant angular velocity of 60 deg/sec were collected for each movement, each suit, and each astronaut.

The custom indirect calorimetry system consisted of a mass spectrometer, portable computer/data acquisition system and flowmeter. Gas concentrations were measured by a Perkin-Elmer Medical Gas Analyzer/Mass Spectrometer (Model 1100). With the spectrometer connected to a sample catheter placed in the output port of the suit ventilation/gas supply control console, suit output O<sub>2</sub> and CO<sub>2</sub> concentrations were continuously monitored. By using a Data Translation DT-707/DT-2801 analog to digital conversion system, the analog voltage output from the mass spectrometer was interfaced to a portable computer (Toshiba T1200).

Using data acquisition software (Laboratory Technologies Corporation LABTECH NOTEBOOK), data was sampled, manipulated, stored on a hard disk, and displayed real-time on an EGA color computer monitor. In addition, the software was programmed to correct for standard temperature and pressure dry conditions and continuously compute, display, and store the metabolic rate of each astronaut.

During the efficiency testing, steady-state metabolic rates were reached and could be compared across suits and within astronauts. When an astronaut reached a plateau and then reached either a 65 percent of peak VO<sub>2</sub> value or a test bout duration of 10 minutes, the fatigue trial was halted. Elimination of the transitory first and last minute from the metabolic rate charts provided an interval of steady-state work that ranged from 3 to 8 minutes. Peak and mean metabolic rate values were then collected from this interval.

## DISCUSSION

As illustrated by a resulting maximum achieved mechanical efficiency of 3 percent, space-suited work during whole body water immersion is very inefficient. Any factor which limited torque input or elevated metabolic rate decreased the mechanical efficiency of performing the movement. While some of the energy consuming components of neutral buoyancy suited work (such as body stabilization, resisting suit inertial forces, and an increased level of anxiety) exist in the space environment, the work done against an induced drag force has no counterpart. The drag force on a moving body through a medium is proportional to one-half the density of the medium multiplied by the square of the velocity multiplied by the projected area of the body. As a result of the medium being water (1.0 kg/m<sup>3</sup>), the angular velocity (60 deg/sec), and the large circumference of the suit's arm segments, the induced drag force generates considerable resistance to movement and can, therefore, explain in large part the very low observed mechanical efficiencies. The effect of the drag force both limits torque production and raises the metabolic output as compared to working in a vacuum. It should also be noted that torque

production measurements from this study were of the same magnitude and range as those in previous torque measurement studies using the same underwater dynamometry system.

Also, error in measuring the metabolic rate as well as creating an EVA work simulation that required higher than actual EVA work rates could contribute to a low observed mechanical efficiency. However, several studies made to evaluate metabolic rate during actual EVA show evidence that the average metabolic rates collected during the simulated EVA fatigue trial were higher, but the range of collected rates correlated well with actual EVA ranges. For example, the range of metabolic rates achieved in the shuttle suit (29.6 kPa) covering the four simulated EVA movements were 245 Kcal/Hr (.85 L/min) to 597 Kcal/Hr (2.06 L/min) with an average rate of 386 (+/- 25.4 SE) Kcal/Hr (1.34 L/min +/- .089 SE). The average metabolic rate reported by Waligora and Horrigan, 1975, during Apollo EVAs was 235 Kcal/Hr (ca. .81 L/min). Waligora and Horrigan, 1977, reported that Skylab EVAs averaged 238 Kcal/Hr (ca. .82 L/min). However, more recent reports (Horrigan, et al., 1985) show that Shuttle EVAs average a somewhat lower 197 Kcal/Hr (ca. .68 L/min). Interestingly, the Soviets report comparable EVA metabolic rates averaging 232 Kcal/min (ca. .80 L/min) with a suit that has a main operational pressure of 40 kPa (Barer, 1989). The metabolic rates recorded throughout these Apollo, Skylab, Shuttle, and Soviet EVAs range from a benign 60 Kcal/Hr (.21 L/min) to a vigorous 720 Kcal/Hr (2.5 L/min). The method developed for measuring the metabolic rates of subjects during space-suited whole body water immersion and the work requirement of the EVA fatigue simulation produce metabolic rates that fall within the range of actual reported EVA rates.

Future studies should address and examine the contribution of the drag force on energy expenditure and measure peak  $VO_2$  consumption and mechanical efficiency while performing specific arm-dynamometry work tasks unsuited. By obtaining a measure of the suit's operational mechanical efficiency, a transfer function for better describing the work capabilities of the astronaut in the suit could be defined. Horrigan, et al., 1986 shows that when metabolic rates measured during the specific space construction tasks of the EASE/ACCESS flight experiment (Flight 61-B) were corrected for body weight, they were almost identical for the two crewmembers. During the ACCESS activity, Crewmember EV1 had a rate of 6.0 BTU/lb/Hr (11 ml/kg/min) and Crewmember EV2 had a rate of 6.5 BTU/lb/Hr (12 ml/kg/min). As mechanical efficiency normalizes work capability, future studies involving a larger number of subjects could easily address intrasubject and between measures variability.

Also, in calculating the net metabolic rate for the fatigue simulation, the resting rate was established while the astronauts were suited and in the pool. This resting rate parameter could be erroneously high due to the possible anxiety of being underwater and dependent on divers for control and stability. Therefore, our efficiency results could actually be inflated because a lower resting rate would increase the net metabolic rate and lower the observed mechanical efficiency. Another addressable question should be the contribution of anaerobic metabolism to periods of steady-state work. This unaccounted for energy also lowers the observed mechanical efficiency. With the effects of drag and other non-operational energy consuming components accounted for, evaluating the mechanical efficiency of work in a neutral buoyancy environment provides a convenient method for comparing space suits, or other pressure suits, and specific work tasks or movements.

## RESULTS

Average torque transmission,  $T\{N\cdot m\}$  (figure 2), was collected along with peak and average metabolic rate,  $MR\{L/min\}$  (figure 3), for each astronaut in each suit and during

each movement. Mechanical efficiency was calculated by starting with the general definition of power output divided by power input. However, a calculation of net mechanical efficiency was actually made as a better representation of performance above a resting metabolic rate. The net mechanical efficiency therefore became the power output divided by the metabolic rate above a resting state. The power output was the torque measured on the dynamometer multiplied by the constant angular velocity of  $60 \text{ deg} \cdot \text{sec}^{-1}$   $\{\pi/3 \text{ rad} \cdot \text{sec}^{-1}\}$ . The metabolic rate above rest was the difference in testing and resting metabolic rates (MR minus MR<sub>rest</sub>). Therefore, mechanical efficiency was calculated and graphs were plotted for each astronaut in each suit and during each movement. Figure 4 illustrates the mean mechanical efficiency achieved by the astronauts in each of the three suits during the EVA ratchet wrench crank and push movements.



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**Astronauts**

A1  
A2  
A3  
A4

**Phase 1**

Resting metabolic data  
taken during weigh-out  
period

**Space Suit Assemblies**

Shuttle Suit  
MKIII  
AX5

**Phase 2**

Fatigue Trial/Efficiency Test  
Test duration: 10 min. or  
65% fatigue

**Movements**

(randomized)  
EVA Ratchet Wrench Crank  
Elbow Flexion  
Shoulder Rotation Med-Int  
EVA Ratchet Wrench Push

Figure 1. Efficiency Test Protocol (WETF Neutral Buoyancy Environment)

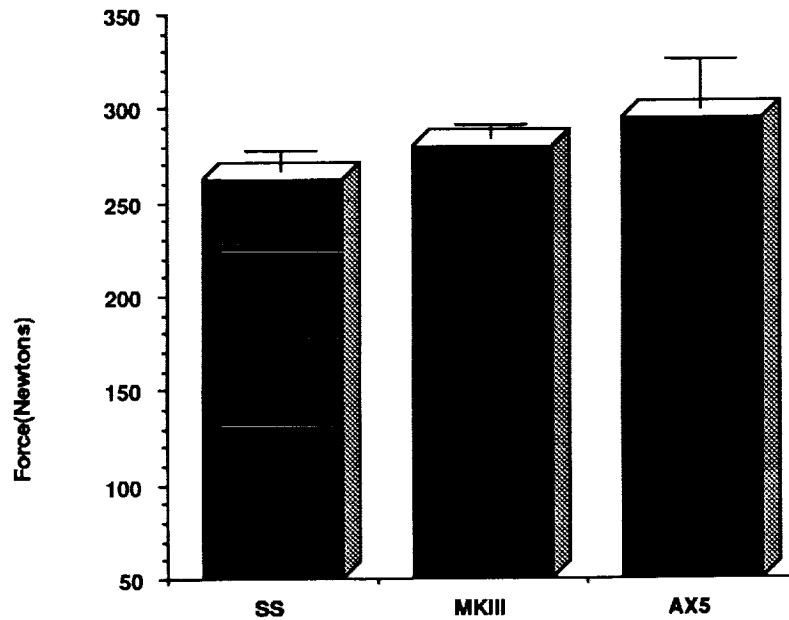


Figure 2. Average Dynamic Force Production During the Ratchet Wrench Push

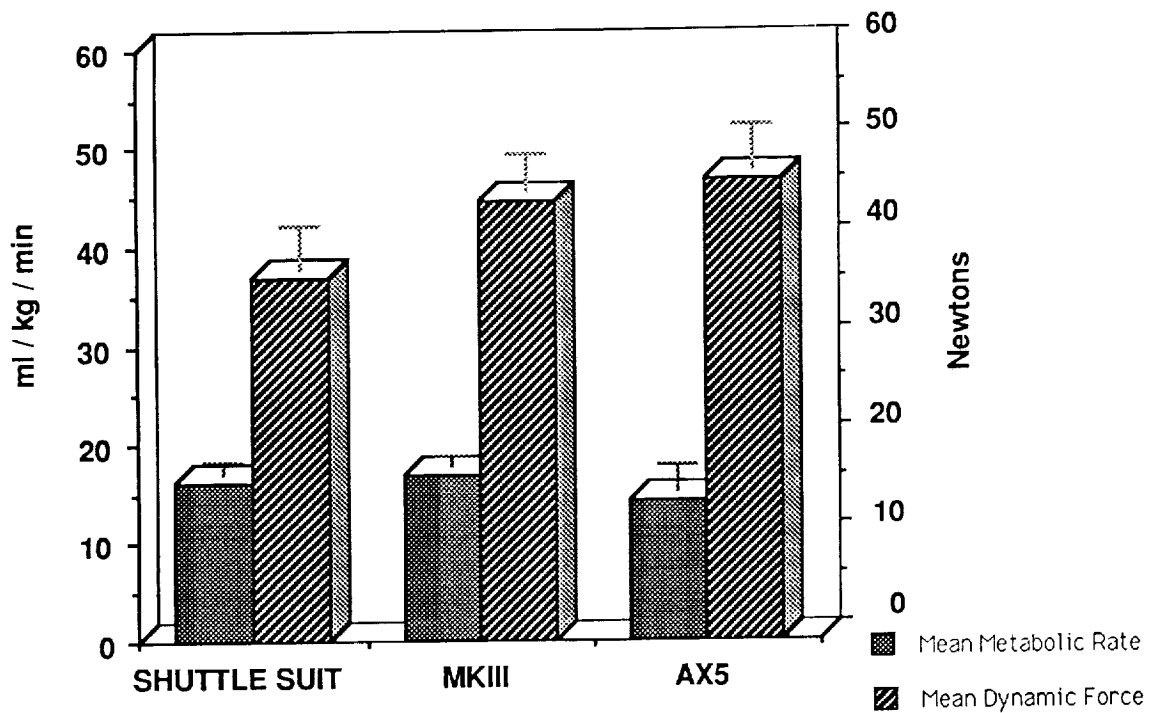


Figure 3. Ratchet Wrench Push:  
Mean Metabolic Rate and Mean Force Production During Fatigue Trial

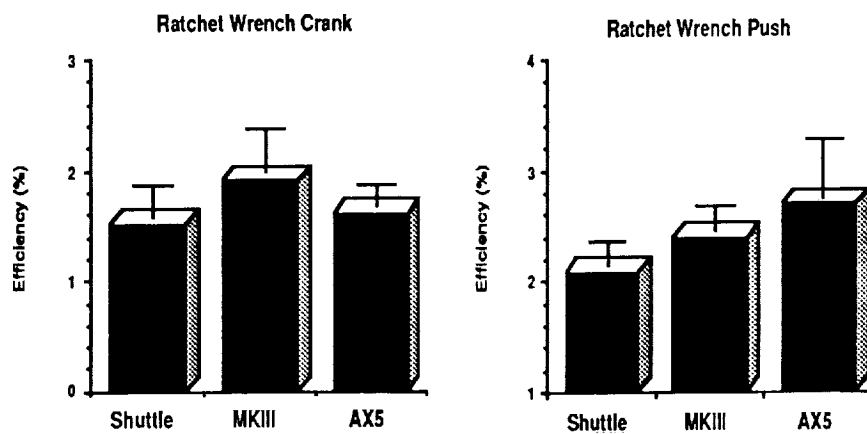


Figure 4. Mean Mechanical Efficiencies Achieved in Each Suit

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