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SUB-OPTIMAL PERFORMANCE REGIMES
- DYNAMIC INTEGRATED SIMULATIONS -

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ABSTRACT

Human performance is the essential element of manned space flight. Manned space flight need not exist were robots or other devices sufficient to accomplish our specific goals in space. However, we know that humans are required for certain tasks, and we also know that the costs associated with humans in space are high. Therefore, anything which can be done to lower costs and improve human performance without jeopardizing safety are in the best interests of manned space flight. We advocate the use of simulations, not only to prepare and train for mission operations, but to analyze and improve the Human Factors aspect of space systems design. We herein describe the steps necessary to create these simulations and the anticipated benefits.

INTRODUCTION

On June 30, 1988, two cosmonauts attempted to repair a failed X-ray detector outside the Mir space station. This unplanned and unrehearsed Extravehicular Activity (EVA) failed. It failed for a number of reasons: the main wrench snapped, physical exertion rates exceeded the cosmonauts' level of conditioning, the planned repair time was too short, and translation to and positioning at the repair site were inadequate. Unplanned EVA is and will likely remain an element of space operations. How can the risk of these unplanned EVA's be reduced, and how can success be assured?

While available tools and cosmonaut physical conditioning are a function of prior mission planning, the execution of a unique and unrehearsed activity could be simulated and rehearsed on board a spacecraft during the mission. These unplanned activities will always be less than optimal: procedures will be devised in real time, rehearsals will be time constrained, and the ideal tools or techniques may not be available.

The translation, the positioning, the required tools, the procedures for the aforementioned Russian EVA could have been rehearsed, IF the cosmonauts had available to them a simulation which accounts for unusual or sub-optimal performance. By simulating human repair of the X-ray detector, the unforeseen difficulties could have been revealed, optimum translation to the repair site could have been determined, task protocol could have been mapped out, and the tool function and repair sequence could have been specified. In short, a simulation embodying sub-optimal human performance, available to the on-orbit and ground support crews can reduce risk and improve man-machine optimization. **This same man-machine optimization, and accounting for human factors, can offer the same benefits in training for a mission, as well as improve the design process itself.**

SUB-OPTIMAL PERFORMANCE

Human performance for space systems is currently predicated on the **optimal** or maximized ideal abilities of the crew. These optimal physical performance states are, in conjunction with the legacy of past EVA's, defined by anthropometric measurements of isolated muscle and joint motions. Much data currently exists which describes isolated human joint performance. This data has been acquired through the use of dynamometers in which the muscles acting upon the joint have been worked to total fatigue. This action defines an upper (in the absence of artificial stimulants such as internal adrenaline or external steroids or amphetamines) limit to performance *for that particular joint in that particular motion.*

Isolated joint motion measurements are useful and necessary to determine kinetic parameters such as range of motion, overall joint/muscular strength, and contribute to a population-wide anthropometric database. These databases are used to specify average body sizes and strengths. Unfortunately, isolated joint strength is less than adequate as a predictor for overall body performance capabilities. Using isolated joint strength and fatigue as an overall predictor of human performance is analogous to equating a football half-back's speed in the 40 yard dash to his ability to take hand-off's, weave and avoid tacklers, and score touchdowns - useful, but hardly as comprehensive as desired.

No integrated performance models or measured kinetic data, based on overall body musculature, exists to the extent that predictions can be made based upon a set of simple motions. Yet, predictions based on an integrated, less-than optimal performance regime are absolutely essential to optimizing the use of crew time and improving man-machine interface. The physiologic and kinetic dynamics of complex motions, such as pole vaulting, or perhaps more relevant to space systems, grappling errant satellites, is beyond our present capability to model, and more importantly, appreciate with regard to fatigue, or possible injury.

Why attempt to predict overall human physiologic performance? Consider the example cited above concerning the football player. Suppose it were possible, given a number of variables (non-infinite, but non-trivial) such as extent of injuries, fatigue states in each quarter of the game and others, to predict how well a halfback could be **expected** to carry the ball. Suppose further that in knowing this, the player's coach could **tailor** the offensive strategy to take advantage of predicted capabilities and mitigate **anticipated** fatigue or weaknesses. Clearly, this ability to carefully design a **performance regime** would seem advantageous to sports professionals, particularly if one's opponent had this predictor...

More to our interests, space systems designers, and in particular, mission planners must predict human performance. This is particularly important with regard to EVA's. This is also important, but less apparent, in reducing operations costs for ground processing. Much experience is embodied in the training protocols currently used to ready astronauts. Much is also needed, both in the realism of training, particularly in the intractable problem of force feedback for microgravity simulations, and in appreciation for and predictive nature of human performance capabilities.

Mission planning and training are not the only important reasons for predicting human performance. Another is systems design. Human Factors analysis and design is an attempt to coordinate and optimize human with machine. Human factors analysis of design can reduce operations costs by streamlining maintenance and refurbishment tasks. All too often, a man-machine interface is based upon instantaneous, static relationships, or worse, the assumption that if an action is not to be performed with great frequency, performance near the limit of human capability is acceptable. This ignores factors such as fatigue, boredom, information overload, and stress, both physiological and psychological. This philosophy also assumes that a person trained for that task actually performs the task. For cockpit operations, this is usually the case, for maintenance or logistics activities, or for a design such as a workstation where a multitude of persons must interact, this philosophy is less than realistic.

Obviously, humans seldom perform at peak output, or do so only for very limited periods of time. Even at peak performance, the level of which is often determined by isolated or discreet actions, such as a stress test, the influences of off-nominal conditions are not taken into account. Most of the time, astronauts (and people in general) perform physical and mental activities well below the upper limit of physical exertion and concentration. What then must be done to improve training and design such that non-optimal performance regimes, which must occur for the majority of the time, are accounted for? One approach would be to exhaustively measure and monitor every potential crew person to determine his or her exact physical capacities. This can be done where crew populations are small, tasks are few and specialized, and the possibility of excursions from mission plans are low. Clearly, this is not the case even for Space Shuttle missions. It is certainly not possible if we believe that the exploration and exploitation of space implies a greater frequency of routine access by people who embody diverse skills and capabilities.

Astronauts chosen and trained for Intra-Vehicular Activities (IVA) and EVA are certainly very capable, both physically and mentally. The success of manned space has amply demonstrated this. However capable space crews are, there still remains the uncertainty associated with unforeseen complications, effects of fatigue, psychological stress, environmental and equipment constraints, and the influence of unusual postures on the abilities of a crew to complete a certain task or mission. We have been fortunate for the caliber of our space crews in that insurmountable difficulties have been few. **As our goal is to improve safety and maximize the useful work space crews can perform, we must be able to predict with greater accuracy what level of physical performance we should realistically expect, not what are the extreme limits.**

An approach to establish human, sub-optimal performance capabilities is to use predictive models. Simulations exist wherein the designer or task planner can specify actions, animate a simulated human figure, and **visually** examine human factors issues associated with those actions. This is being used currently, with great success, for EVA planning. Missing from these simulations is quantitative feedback to the designer or planner of simple human physical ability: can we predict that a human is capable of actually performing the muscular activities required by the mission planner? Are the postures and movements dictated by the task actually possible? Are there alternative scenarios by which high-stress, potentially injurious or fatiguing actions can be minimized? Is there a low-cost technique, as an alternate to hard mock-ups and use of neutral buoyancy tanks, by which analysis of sub-optimal performance can be realized? We believe that improvements on current predictive simulations can answer these sub-optimal performance questions.

SIMULATION REQUIREMENTS

To conduct these sub-optimal predictions, we anticipate the use of simulations. Issues associated with using simulation to analyze human performance are:

- Application of anthropometrics to human simulations
- Integration of joint strength to overall performance
- Effect of off-nominal conditions such as posture, fatigue, and psychological stress
- Environmental constraints
- Translation of one-g data to effects in micro-g
- Closed-loop, interactive multi-person simulations

Our concept **links** the dynamic strength anthropometrics and simulation techniques with a functional feedback output based on optimum performance. Combining industrial engineering practices and standards with the NASA expertise and our own vision of performance metrics, we propose to establish sub-optimal performance parameters which can then be used to analyze relevant task scenarios for efficiency and effectiveness. Instead of predicating IVA or EVA on the upper limits of physical performance, we will predicate them on **realistic** and quantified expectations. Most significantly, we envision the gradual evolution of human factors in which space systems are more optimized with regard to man in the loop.

SIMULATION PROCESS

Simulations, such as JACK™ or COMBIMAN, exist which model and animate the human form, are adjustable across the spectrum of human body sizes, and embody some analytical attributes. Range of motion, inverse kinematics, egocentric viewpoint are attributes current simulations possess. These simulations will be assessed for suitability and where necessary, evolved to meet the simulation-defining criteria delineated below. The goal in establishing these criteria is to improve simulations such that quantification of the effects of off-nominal conditions are inherent in the analysis. Our concept for integrating anthropometrics, dynamics and kinematics is shown in Figure 1.

SIMULATION CRITERIA

1. ANTHROPOMETRIC DATA

A sizable database of isolated joint motion, muscle fatigue, and likely a diffuse body of sports-oriented data exist. The NASA, for example, possesses and uses anthropometrics to model EVA tasks. The acquisition of a statistically significant set of motion data across a specific joint must be identified, sifted, and made readily available.

2. DYNAMIC MOTION ALGORITHMS

Anthropometric information must be translated and combined so as to be useful in the dynamic realm. At first, these algorithms will seek to duplicate simple joint function. Following this, the various muscle groups which act across a joint will be "summed" to create a kinetic model which closely mimics actual joint dynamics. Currently available anthropometric simulations will be assessed for applicability.

3. FORCES ACROSS JOINTS

Vital to the end use of simulations to model sub-optimal dynamic behavior is the verification and fine tuning of the joint motion models. Verification will take the form of measuring muscle tension and force across a joint engaged in a simple movement, such as elbow flexion.

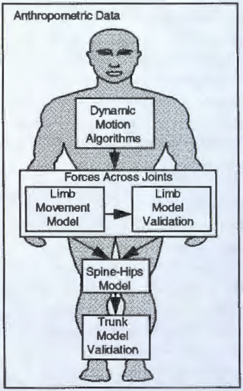

FIGURE 1. MODEL INTEGRATES DYNAMICS WITH ANTHROPOMETRICS

We propose to verify muscle forces throughout the range of joint motion thereby fine-tuning the algorithms AND defining a *performance "topography"* of the joint in question. We define performance topography as anthropometry merged with physiological dynamics.

4. MODEL LIMB MOVEMENT

Concurrent with algorithm verification, joint motion descriptors must be "linked" such that performance topography for each joint is a function of multiple joint-joint interaction. It is intuitive that a weak biceps muscle cannot lift a heavy weight no matter how powerful are the shoulder muscles. So too must our individual joint algorithms be *interdependent* such that overall muscular ability, within the context of our envisioned simulations of real-world physical performance, is limited by the "weakest link in the chain." This linking also has implications for the overall metabolic loads placed on the body by physical activity.

5. LIMB MODEL

Similar to the verification task cited for individual joint movement, the integrated model of limb motion and performance topography must be validated with physical measurements. Sports medicine offers tools by which this verification can take place. Golfers, for example, can have their swings analyzed using biomechanical sensors and video to determine glitches in the motion. Orthopedic physical therapy often uses computer assessment of motion. Both techniques have applicability to our verification.

6. ANTHROPOMETRICS OF SPINE & HIPS

Forces through the spine and hips are essential elements to realistic simulations of human animation. Without an integrated force-reaction force, muscle and joint loads of the limbs cannot be comprehensively summed and performance rates calculated.

7. TRUNK MODEL

Again, model accuracy must be verified with actual performance data. Once the integrated trunk model is verified, we can then apply the sub-optimal attributes to determine the effect on performance.

SUB-OPTIMAL ATTRIBUTES

The goal is to determine to what extent and how each attribute influences and degrades ability. Once an integrated human model is verified, sub-optimal attributes must be "built-in" to the model to enable the analysis of off-nominal performance. These attributes, listed below, have a cumulative effect on the ability of a human to conduct work. None of the listed attributes have effects independent of another. Most are highly variable across a spectrum of individuals. All contribute to the extent optimum performance is effected. Some of the attributes listed and described are more well understood than others, some have until now defied quantification or have not been important. As we contemplate longer missions with more complicated goals, human factors and man-machine optimization must take greater precedence in system design, mission planning, crew selection and training, and simulation. Incorporation of the interactive effects of sub-optimal states is a vital element in the utility of simulations.

POSTURE - Posture has a profound influence on the ability to perform work. Posture and its influence is not a static quality; posture changes during physical activity and is influenced by the local environment, i.e. microgravity. As such, the effect of postural changes is dynamic. The effect of posture can be either to improve or erode the ability to perform a task.

FATIGUE - Fatigue is cumulative over the short term physically, and over the long term cognitively. Fatigue levels are a function of physical conditioning, mental training, health, age, psychological, and environmental factors. The physiological effects of microgravity deconditioning are a fertile area of inquiry with regard to fatigue.

INJURY - Clearly, injury diminishes the ability to perform. Life threatening or serious injury obviously prevents the person from even caring for him or herself. Minor injury or illness does not necessarily remove the crewperson from the tasks at hand, but certainly reduces performance. The degree to which performance is reduced is variable between individuals and difficult to predict and quantify.

AGE - Physical performance degrades with increasing age, although the physical effects can be somewhat mitigated by the increased mental and analytical abilities gained through experience. Age effects between individuals are highly variable and difficult to quantify. These variable effects of age underscore the importance of task planning the effective training.

CONDITIONING - The extent of cardiovascular conditioning, as an isolated attribute, can be determined through stress testing. This level of conditioning can act to mitigate age effects and delay fatigue. Clearly, micro-gravity deconditioning will have a profound effect as mission durations increase.

GRAVITY FIELD EFFECTS - Micro-g simulations, with the appropriate feedback effects, are a critical need. Current underwater training provides the neutral buoyancy aspect, but cannot impart the verisimilitude of micro-g. Human performance in microgravity is of keen interest to the mission planner, and hence the human factors analyst. A wealth of information exists which qualitatively describes human performance in micro-g, and much of this information is applicable to our interests. A significant body of biotelemetry has been acquired during the history of space flight. This homeostatic, dynamic and metabolic data is a vital element in the quantification of performance. Of interest is the interrelationship between performance in micro-g and cardiovascular conditioning.

EQUIPMENT CONSTRAINTS - Equipment is a well defined constraint but which can have an undefined effect depending on how it is used. Equipment can range from simple hand tools to space suits. Hand tools have less of a long term, overall effect since tools which do not perform well can be modified. Space suits, on the other extreme, cannot be readily modified. The effects of wearing a space suit on task performance are profound and the subject of intense preparation and training. Thus, the omnipresent nature of equipment and its utility has a profound effect on human performance, an effect essential to the overall simulation and prediction.

SUMMARY

The use of simulations for human factors analysis is predicated on improving the safety and operability of manned systems. Simulations have been used to good effect in the planning and training for EVA. The brilliant success of the Hubble repair mission was in part due to the use of simulations for training. This is a noble beginning.

We advocate the increased use of simulations for training, and have suggested a plan to enhance the simulations now available. **Specifically, we urge the development of analysis tools by which sub-optimal human performance can be used to more accurately assess mission task planning, and as an integral aspect of the design process.** We have embarked on just such a course. By using sub-optimal performance analysis in the design process, a more accurate assessment of design functionality and useability can be performed. When concurrent with the design process, the operability of a vehicle or system is improved, and developmental costs are reduced due to the immediate resolution of potential human factors issues.