A Comparison of Methods for Assessing Space Suit Joint Ranges of Motion

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Through the Advanced Exploration Systems (AES) Program, NASA is attempting to use the vast collection of space suit mobility data from 50 years worth of space suit testing to build predictive analysis tools to aid in early architecture decisions for future missions and exploration programs. However, the design engineers must first understand if and how data generated by different methodologies can be compared directly and used in an essentially interchangeable manner. To address this question, the isolated joint range of motion data from two different test series were compared. Both data sets were generated from participants wearing the Mark III Space Suit Technology Demonstrator (MK-III), Waist Entry I-suit (WEI), and minimal clothing. Additionally the two tests shared a common test subject that allowed for within subject comparisons of the methods that greatly reduced the number of variables in play. The tests varied in their methodologies: the Space Suit Comparative Technologies Evaluation used 2-D photogrammetry to analyze isolated ranges of motion while the Constellation space suit benchmarking and requirements development used 3-D motion capture to evaluate both isolated and functional joint ranges of motion. The isolated data from both test series were compared graphically, as percent differences, and by simple statistical analysis. The results indicated that while the methods generate results that are statistically the same (significance level p= 0.01), the differences are significant enough in the practical sense to make direct comparisons ill advised. The concluding recommendations propose direction for how to bridge the data gaps and address future mobility data collection to allow for backward compatibility.

Nomenclature

deg = degrees
in. = inches

I.   Introduction

S pace suit design is rooted in aviation history with the first practical American garment arriving on the scene in 1934, as a result of partnership between the aviator Wiley Post and the B.F. Goodrich Company (Thomas & McMann, 2006). The boom of the of space suit design however rests solidly in the 1960s as engineers and scientists across the United States worked to create the suits that would take American astronauts into space and ultimately to the moon with hopes of Mars. As each suit prototype was fabricated, both the manufacturers and NASA invested significant time to benchmark suit mobility during the completion of representative extra-vehicular activity (EVA) tasks. As the complexity of planned EVA tasks increased from Gemini to Apollo to Space Shuttle and International Space Station Programs, the importance of designing suits for mobility became more obvious, but the methods for evaluating suit mobility remained some what rudimentary relying on hand measurements with goniometers and/or a protractor and still photographs with results often being highly dependent upon the consistency of the person actually taking the measures for identifying and aligning the joint axes to be compared. During the beginnings of the Constellation Program, NASA shifted gears to 3D motion analysis aided by the use of the Vicon motion capture system. The hope was to collect dynamic range of motion data that would be more representative of the entire range each suit could achieve when not bound to hold static poses for traditional still photography. Now, with the transition from the short lived Constellation Program to the decidedly more technology development focus of the Advanced Exploration Systems Program, NASA is attempting to use the vast collection of mobility data from 50

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years worth of space suit testing to build predictive analysis tools to aid in early architecture decisions for future missions and Exploration Programs.

To produce a useful tool for predicting human mobility given a specific combination of mobility features, one must of must understand how the base data set was acquired and if and how data generated through different methodologies can be used interchangeably. The following sections of this paper provide an overview of the different methodologies available to collect and analyze mobility data and then focuses on a comparison of data collected for the Space Suit Comparative Technologies Evaluation Report in 2000 (Ross, 2000) and the CSSS benchmarking and requirements development project in 2009 (England, 2010). These two test series are of particular interest because not only do they evaluate the same suits by two different methods, photogrammetry and Vicon, but they also have a test subject in common. Data from the cross-over subject should yield more direct results as complicating factors such as test subject unsuited mobility, suit fit, and experience can be eliminated for within subject comparisons.

II. Background

There have been numerous studies to quantify human mobility with motivations ranging from understanding physiology to improving athletic performance to the design of apparel and protective clothing. The majority of the studies define mobility in terms joint range of motion (ROM) as measured by the relative movement between body segments. The methods for collecting data range from simplistic hand measurements with a protractor or goniometer to more complex digital data collection and software aided analysis. For the protective clothing studies, which includes space suits, the acceptability of the garment tends to be gauged by comparing test subject ROM in the minimally clothed versus fully suited conditions for both static and dynamic ranges.

For the final down selection of the Apollo space suit assembly (SSA) design, Jones reported on an elaborate series of testing that provided weighted scores for suit performance on each subtest in the overall evaluation (Jones, 1966). Some of the more heavily weighted subtests of his testing were mobility evaluations. Jones reported that mobility was measured as functional reach inside a high fidelity Crew Module simulator and three different analyses of isolated joint ROM outside the vehicle mock-up. The isolated data were collected by real-time measurements with a goniometer as subjects held static postures in each joint's extreme ranges of motion. Additionally, multi-exposure photos of subjects posing in postures demonstrating the extreme ranges of each joint motion in front of a grid board (see Figure 1), were taken and later analyzed to determine angular range (a process alternately termed photogrammetry or strobe analysis). To complete his study, Jones also conducted an x-ray study which used the midline of the major bones to directly measure the human joint angles while wearing the suit prototypes.
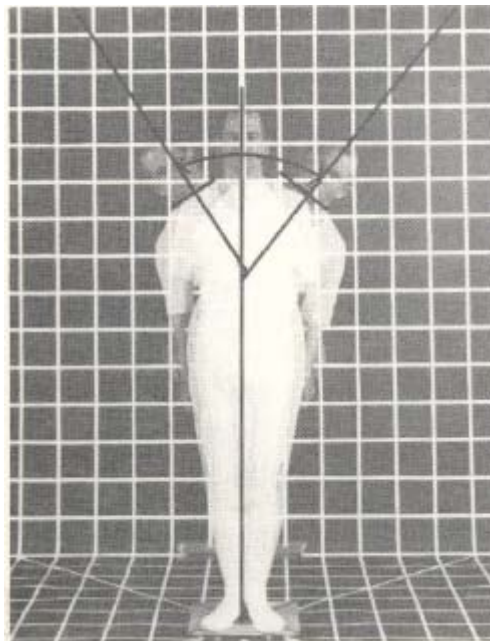

Figure 1: Example of strobe analysis method for minimally clothed subject (URS Corporation, 1974)

One can infer that Jones and his team regarded the strobe method as most accurate as its results were weighted twice as much as the other two methods' results. The strobe method was again employed at the start of the Space Shuttle Program by the URS Corporation in order to evaluate the Apollo A7LB SSA against a new Orbital Extravehicular Spacesuit (OES) for microgravity operations. The conclusions of the URS report indicate that there was significant difficulty in obtaining pure isolated joint movements and that the bulk of the suit led to what the researchers believed was an exaggerated appearance of movement in the photographs. Additionally, the researchers reported that the static poses captured by photography are more representative of the "normal range of motion" than the extreme. This conclusion was attributed to the observation that test subjects were able to over-drive the joints to achieve a greater range but could not maintain the pose long enough to acquire clear still photos (URS Corporation, 1974). More recently, a joint venture between NASA and the Russian Space Agency to evaluate Mars suit concepts in 2004 relied solely on the Apollo era photogrammetry method to evaluate static range of motion for isolated joints. The Mars suit evaluations determined neutral joint positions and angular range by direct measurements taken from still photographs of subjects performing prescribed motions in a plane parallel to the grid board (Abramov, 2005).

As digital technology improved over the last quarter of the 20th century, new forms of real-time motion capture analysis emerged. Some of the most common of the optical motion analysis systems are Dartfish, Simi Motion Capture 3D, Ariel Performance Analysis System (APAS), and Vicon MX. Systems like Dartfish and APAS use digital video cameras and computer vision techniques to create a 2D model of the subject without the use of markers (Brock, 2010). The Vicon system, by contrast, uses reflective marker balls to generate 3D models with the BodyBuilder software. The benefit of the 3D model is that it enables the researcher to collect the complete coupled motion of complex joints, such as the hip and shoulder, throughout the entire dynamic range of motion; this reduces the loss of data outside the "normal range" associated with static ROM collected via photogrammetry (Doriot et al, 2006). However, there are several marked disadvantages compared to manual methods including large capture volumes required, time consuming calibration and start-ups steps, sensitivity to camera vibration, long and tedious post-processing, and, of course, the high cost of purchasing the systems.

The Dartfish system was employed at the Desert Research and Technology Studies 2003 field test to evaluate the efficacy of the MK-III prototype space suit in the performance of field geology tasks but it yielded extremely varied within subject results that the test team judged to be highly erroneous (Ross, 2004). The Vicon system has been used in several test series at NASA Johnson Space Center's (JSC) Anthropometrics and Biomechanics Facility (ABF) since being acquired by the ABF team in 2004. The results of the Vicon test series have been used to aid lunar rover design, evaluate the effects of mass and center of gravity on gait patterns, and benchmarking the mobility of current flight and prototype space suit technologies. However, the author was unable to locate any reports comparing the relatively newly collected Vicon data with the decades of previously collected ROM data on the same or similar space suits.

The Space Suit Comparative Technologies Evaluation Report, which is detailed in the following section, addressed the validity of digital motion capture using the Ariel motion analysis system (Ariel Dynamics). The general conclusions of that testing revealed slight difference between data collected manually and digitally but were generally felt to be comparable. The Ariel Motion Analysis System is considerably less sophisticated than the Vicon system used to benchmark space suit ROM in the Constellation requirements development effort, thus a comparison between the Vicon system and manual measurements is still critical to understanding the extent to which data collected by the two different methods may be used interchangeably.

A. 1999 Prototype Suit Mobility Study – Photo Method
In 1999, JSC's space suit engineering and human factors teams, led by Amy Ross and Dr. Sudhakar Rajulu, respectively, collaborated on an extensive test series to evaluate the performance capabilities of candidate prototype suits with the aim of collecting both subjective and objective data regarding the performance of various planetary space suit mobility joints to aid in the downselction of a mobility system for the next generation space suit assembly (Ross, 2000). One subset of the overall series was the evaluation of suited range of motion during the performance of both isolated tasks. Thirteen isolated movements were performed by each of three test subjects in shirtsleeves and both the WEI and MK-III suits. The motions were performed in an identical manner by each subject to reduce variability in the results. The team captured data both by still photography and digital video recording, but only the still photography method will be presented in detail and discussed here. The photographic data collecting utilized two 6in. x 6in.-gridded boards, one vertical against the wall and the other horizontal on the floor, and two still cameras. One of the cameras maintained a fixed location orthogonal to the vertical grid board throughout the test; second was fixed in position on the ceiling directly above the center of the horizontal grid board. A photo was taken at each extreme that could be achieved and held reasonably stable by the subjects as the isolated motions were performed.

Post-test analysis of the still photographs was completed by printing the photographs onto transparency films, laying the photos of the two extremes of a motion on top of each other on a light table, and measuring the angle difference using a protractor. The method required the analyst to be familiar with the mechanics of the suit in order to properly assume locations for neutral suit positions, joint centers of rotation, and the joint segment centerlines. The results for each individual test subject in each test condition were tabulated to illustrate the total joint range achieved and also used to calculate overall percent differences in mobility when going from the shirtsleeves to suited condition. Lastly, the reported results indicate "smallest effective range" for each suit defined as the smallest maximum range of motion produced by the three test subjects during the performance of isolated joint movements for each suit (Ross, 2000). In addition to the quantitative results, Ross provided a detailed summary of test subject comments and test conductor observations of each test condition. These subjective comments are valuable in understanding contributing factors when the reported angular data for an individual or motion seem out of context when compared to other suited or shirtsleeves conditions. The test conduct comments also aided the present author in understanding how the original test conductor established joint centers and their assumptions of what constituted an 'isolated' motion.

B. 2008 Constellation Suit Requirements Development Study – Vicon Method

With the advent of the Constellation Program (CxP), the NASA Constellation Space Suit System (CSSS) Pressure Garment Team partnered with the ABF to develop a mobility test methodology that would enable rapid benchmarking between suit prototypes, verifiable range of motion requirements for CxP suits, and computer modeling of suit system behavior in a consistent and repeatable fashion. The ABF selected the Vicon 612/SV motion capture system to record the data and the complementary Vicon BodyBuilder™ software to analyze the data. The Vicon set-up used 10 cameras positioned over the capture volume to record the reflections of the 41 marker balls which were fixed to the joint segments of the test subject (see Figure 2).
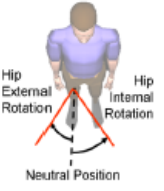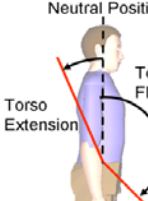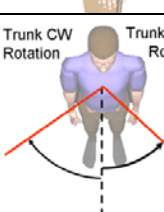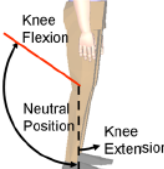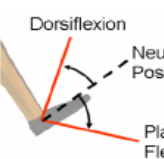

Figure 2. Pressurized WEI (left) and MK-III suits with marker ball set in place

There were a minimum of three markers per body segment on the torso and right hand side limbs that roughly corresponded to biomechanical human body segments; the symmetry assumption was used to greatly reduce data reduction times in post-processing. The same marker sets were used for all test subjects in all conditions. A total of four test subjects (2 female, 2 male) completed a series of 16 isolated and 49 functional tasks representative of CxP mission objectives in the unsuited, WEI, and MK-III conditions. The isolated tasks were standardized to ensure comparable data while the functional tasks (e.g. crawling, walking, kneeling, etc.) were left to test subjects to decide on the best way to complete the task in order to capture outliers. Only the isolated task data were used for comparisons in this paper. The BodyBuilder™ software calculated joint angles by assuming a primary axis extending from the dynamic and static joint segments and measuring the angular travel of the dynamic segment axis relative to its neutral position and the static segment's axis. These measures are illustrated in Table 2, below, along with the names of the two joint segments used to calculate the angle. All of the isolated tasks presented in this paper

were collected without the use of props against which subjects could gain force advantage (e.g. pressing palm against the wall to increase range of wrist flexion/extension).

Table 2: Joint Motions Performed in Digital Data Collection (England, 2010)

Joint Motion	Illustration	Dynamic Segment	Static Segment
Shoulder flexion/extension		Upper arm	Torso
Shoulder adduction/abduction		Upper arm	Torso
Shoulder lateral/medial rotation		Upper arm	Torso
Elbow flexion/extension		Forearm	Upper arm
Hip flexion/extension		Hip	Torso
Hip adduction/abduction		Hip	Torso

Hip (ankle) rotation	Hip External Rotation / Hip Internal Rotation / Neutral Position	Hip	Torso
Torso lean	Neutral Position / Torso Right Lean / Torso Left Lean	Torso	Hip
Torso flexion/extension	Neutral Position / Torso Flexion / Torso Extension	Torso	Hip
Torso rotation	Trunk CW Rotation / Trunk CCW Rotation / Neutral Position	Torso	Hip
Knee flexion/extension	Knee Flexion / Neutral Position / Knee Extension	Shin	Hip
Ankle flexion/extension	Dorsiflexion / Neutral Position / Plantar Flexion	Foot	Shin

In his discussion, England emphasizes that suit mobility measurements "must reflect the fact that altered movement strategies are utilized while wearing a space suit" thus while the ranges of motion achieved in each suit conditioned varied, their ability to functionally perform tasks was unhindered on the whole. He further concludes that the 3D Vicon methodology pioneered by his team will yield both time and cost savings in the evaluation and benchmarking of future prototype suits.

III. Data Comparisons

As indicated in Tables 1 and 2, both test series used the same isolated joint movements to define the ranges of motion, however the signs associated with some joints differ. To minimize confusion, the data were compared as total ranges of motion. The total range for each joint was calculated as the sum of the absolute values of the joint extremes in each direction. For all results shown below, 'overall' refers to the singular value listed as a suit's specific isolate ROM within the two test reports. In both cases, the range of motion was defined as the minimum of

the total maximum ranges achieved by the subjects for the joint of interest. The 'individual' results refer to the ROM data reported for the one test subject who participated in both test series.

The results of the ROM data collected by both manual and digital methods are shown in the comparative column graphs of Figures 4 – 6 for all suit conditions. Data was recorded for all motions in all conditions, thus the absence of a column for any motion indicates 0° total range was achieved.
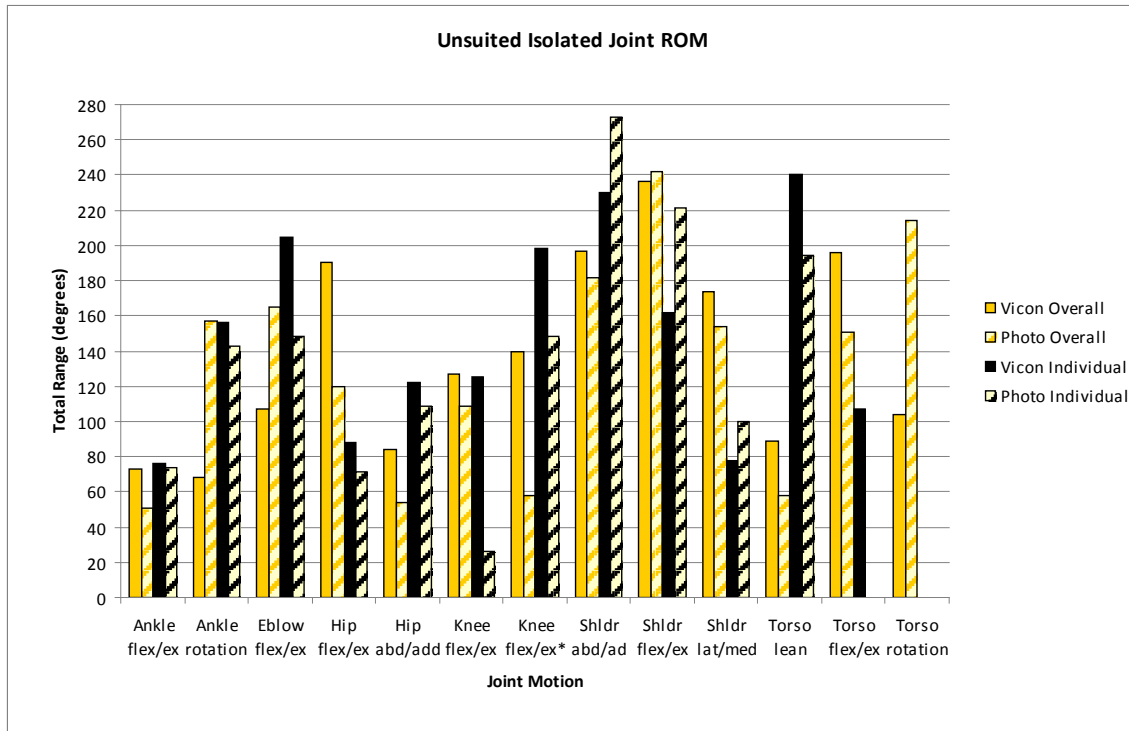

Figure 4. Comparison of digitally and manually collected unsuited ROM data

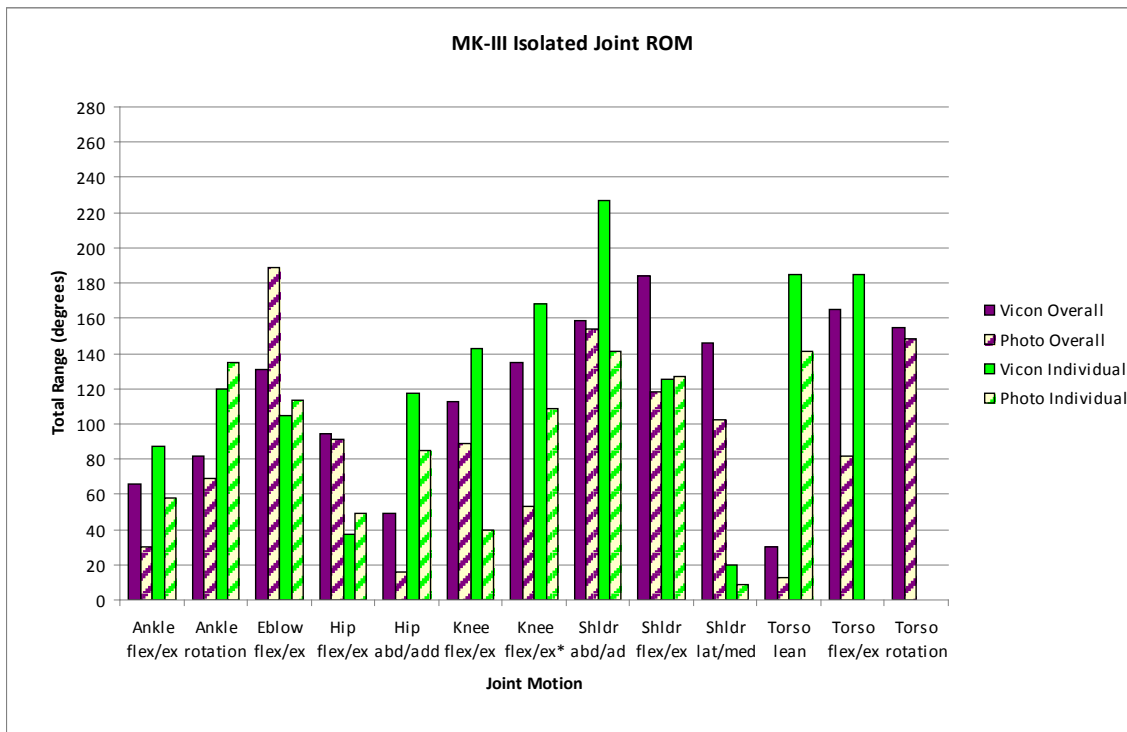American Institute of Aeronautics and Astronautics

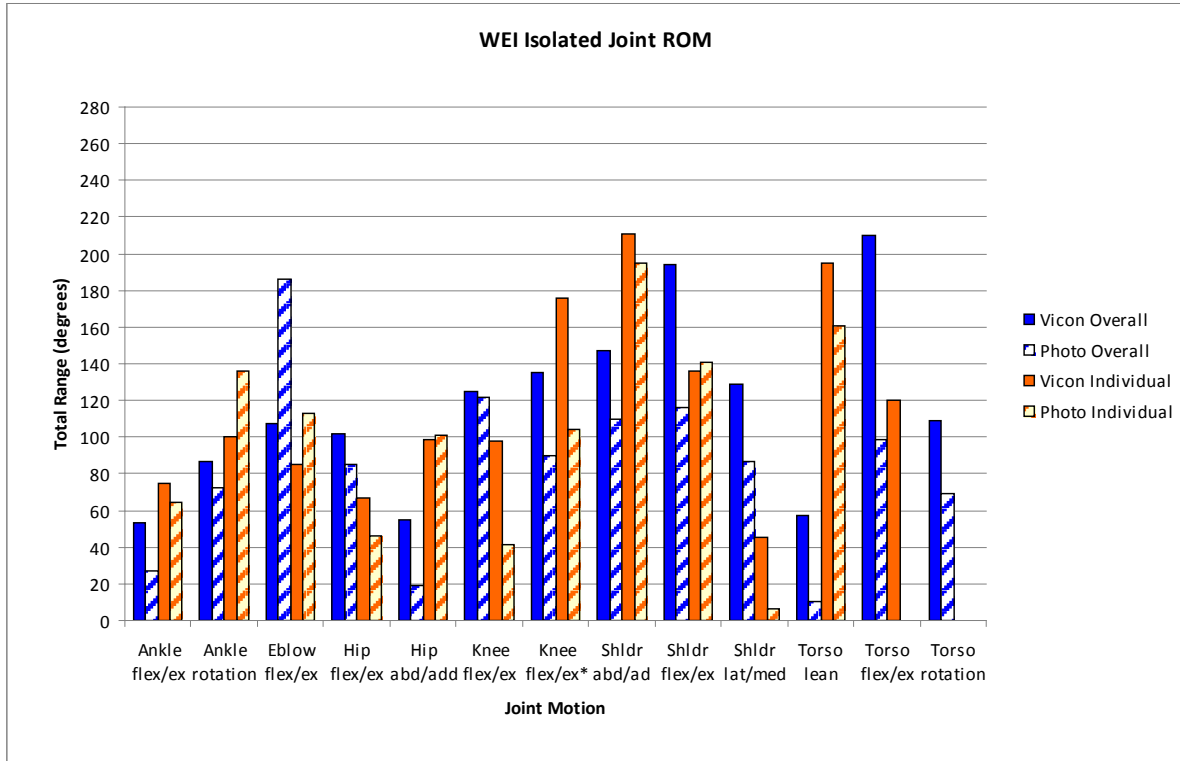Figure 5. Comparison of digitally and manually collected MK-III ROM data

Figure 6. Comparison of digitally and manually collected WEI ROM data

The percent difference between the digitally and manually collect ROM data were calculated as (range_digital – range_manual)/(range_digital)*100. Figures 7 and 8 show comparative results for all suited conditions and all thirteen isolated motions identified in the manual data collection test plan. Negative values indicate that the ROM recorded by the manual method exceeded that recorded by the digital method.

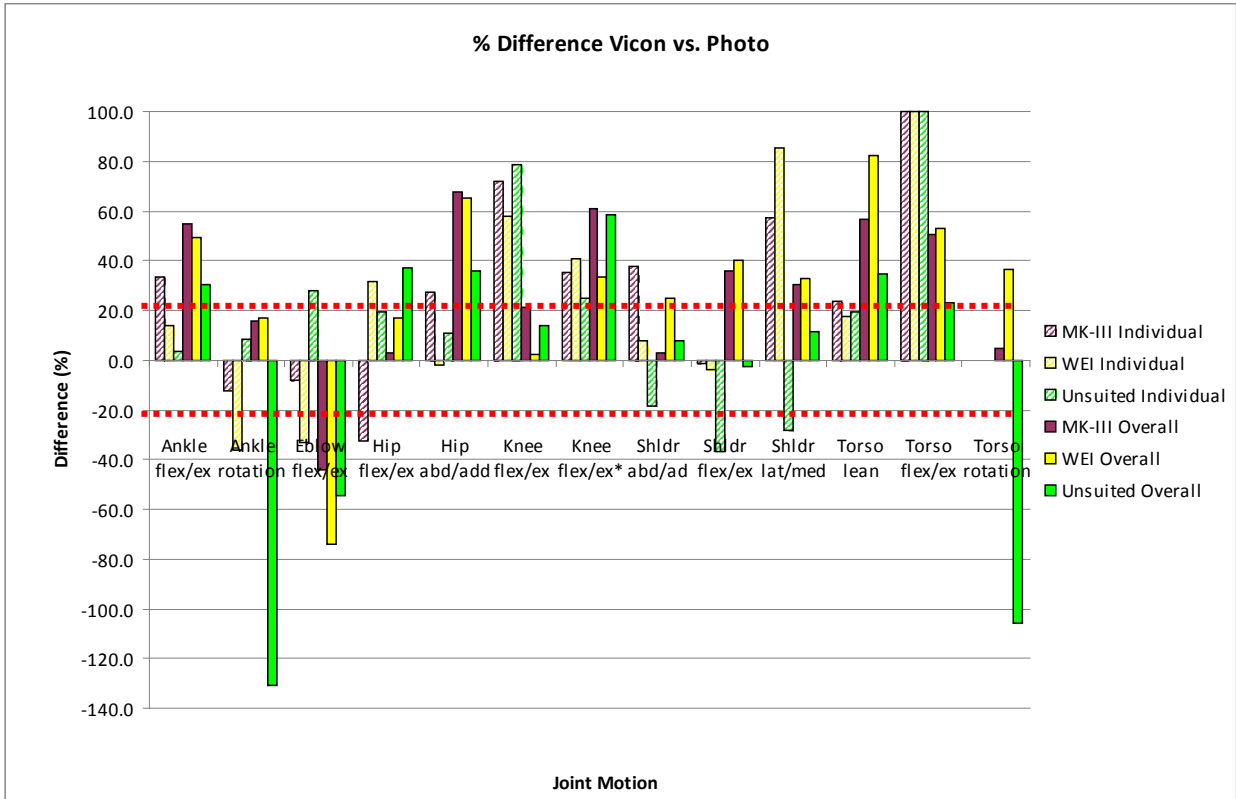American Institute of Aeronautics and Astronautics

Figure 7. Comparison of percent difference digital vs. manual ROM results for each suit condition (dashed red line represents level of practical significance)

A comparison of means using the Student t test for a one-way analysis of the percent difference results by data collection method showed no statistically significant difference between the methods for p=0.01.   A comparison of means using the Student t test for a one-way analysis of the percent difference results by suit condition also showed no statistically significant difference between the conditions for p=0.01. However, when comparing the data against the 20 % practical significance level (meaning all values within 20% difference of each other during requirements verification would be considered the same) established for CSSS requirements the two methods yield practically identical results in less than five test points per test condition for both the overall and individual comparisons. The highlighted cells in Tables 3 indicate values that have exceeded the practical significance level for the percent difference between the Vicon and Photo method results. There is no discernable correlation between which motions achieved practical significance overall versus across the individual results.

Table 3. Comparison of % Difference of Vicon and Photo Results at 20% Practical Significance

Direction	Overall Results			Individual Results		
	Unsuited	MK-III	WEI	Unsuited	MK-III	WEI
Ankle flex/ex	30.1	54.5	49.1	3.3	33.3	14.0
Ankle rotation	-130.9	15.9	17.2			
Eblow flex/ex	-54.2	-44.3	-73.8	8.3	-12.5	-36.0
Hip flex/ex	36.8	3.2	16.7	27.8	-8.1	-32.9
Hip abd/add	35.7	67.3	65.5	19.3	-32.4	31.3
Knee flex/ex	14.2	21.2	2.4	10.7	27.4	-2.0
Knee flex/ex*	58.6	60.7	33.3	78.8	72.0	58.2
Shldr abd/ad	7.6	3.1	25.2	25.0	35.1	40.9
Shldr flex/ex	-2.5	35.9	40.2	-18.5	37.7	7.8
Shldr lat/med	11.5	30.1	32.6	-36.7	-1.6	-3.7
Torso lean	34.8	56.7	82.5	-28.2	57.5	85.6
Torso flex/ex	23.0	50.3	52.9	19.2	23.5	17.4
Torso rotation	-105.8	4.5	36.7	100.0	100.0	100.0

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While there is a statistical equivalence between the Vicon and Photo methods, the compared data cannot be used in a directly interchangeable manner based on quantitative results alone. It's logical to assume that the small sample size for both methods is a substantial contributor to the large range of values reported as the effective range for each suit overall but the sample size cannot account for the variances within the cross-over subject's data. Thus, the focus for finding method-based contributing factors focused on the individual results primarily. Table 4 compares the data across suits and methods to highlight which method generated the greater range for each of the motions; as before, comparisons with percent difference less than 20% are considered equal.

Table 4. Method Generating Maximum Range for Each Condition (Within Subject)

Direction	Test Condition		
	Unsuited	MK-III	WEI
Ankle flex/ex	Equal	Vicon	Vicon
Eblow flex/ex	Equal	Equal	Photo
Hip flex/ex	Vicon	Equal	Photo
Hip abd/add	Equal	Photo	Vicon
Knee flex/ex	Equal	Vicon	Equal
Knee flex/ex*	Vicon	Vicon	Vicon
Shldr abd/ad	Vicon	Vicon	Vicon
Shldr flex/ex	Equal	Equal	Equal
Shldr lat/med	Vicon	Equal	Equal
Torso lean	Photo	Vicon	Vicon
Torso flex/ex	Equal	Vicon	Vicon
# Responses			
Equal	6	4	3
Vicon	4	6	6
Photo	1	1	2

Across all conditions for the individual, when there is a practical difference between the ranges generated by the different methods, it will most often be Vicon that yields the greater range of motion. Looking at the suited results for torso flex/ex and torso lean, it is obvious that the Vicon marker set is directly the cause of the seemingly larger ranges. The Vicon method measured torso flex/ex and lean by comparing the relative motion of the torso plate (located on center chest) to the hip plate (located between the thigh bearing and knee joint) whereas the photo method compared motion of the suit upper torso (relatively same as Vicon location) to the center of the suit brief. Thus the Vicon method accounted for the combined mobility of the hips and waist elements to achieve torso flexion which is considerably more than the capability of the waist element alone- particularly for torso lean because the only torso adduction/abduction features for both suits are located in the hip elements.

Differences in the way in which the motions were performed appear to be the cause of the greater ranges generated by the Vicon method for both styles of knee flexion/extension. For the 'functional' range (noted by * in Table 4), the photo method collected the range at standing and kneeling static positions. The 'functional' measure for Vicon however is not directly assigned to a kneeling task; it could have been the result of any of the 49 functional motions that were performed. The prescribed method for isolated knee flexion/extension was slightly different as well because Vicon ranges were again collected as dynamic sweeps as opposed to static poses and the Vicon method also allowed the test subjects to support themselves by holding onto the back of a chair as they performed the sweeps. The fact that the only practical difference occurred with MK-III, leads one to believe that the increased stability was enough to off-set the weight of the comparatively heavy MK-III and allow the subject to use the full joint range of motion.

Hip flexion/extension were performed in an almost identical manner across test methods and were thus ruled out as the cause of the variance between ranges recorded. Interestingly, it is only the WEI suit that shows a significant difference in recorded ranges (only 8% difference between methods on MK-III). When suited, hip flexion/extension is not a pure planar motion; it requires a combination of hip element flex/ex and adduction/abduction which, when viewed from the front, makes the knee push away from the saggital plane as the hip flexes. The space suit community commonly refers to this mix of motions within the performance of an isolated task as 'programming.' When using the photo method, the extent to which the knee abducts or adducts is impossible to tell and thus it is quantitatively ignored when the full range is recorded. With the Vicon method, however, the analyst self-selects the degree to which they feel the knee strays from the planar motion and thus the maximum flex/ex is actually measured as the angle between the two resultants generated from the summation of motion in the two planes. The data

processing required to achieve this result is quite complex and not easy to tease out for 'better' comparisons nor are the assumptions for processing identical across suit configurations. These differences in post-processing between the methods to account for joint programming are likely a significant contributor to the range differences.

The differences for elbow flex/ex, ankle flex/ex, hip add/ab, and shoulder ad/ab are not as easily explained. It is possible that the subject had a different boot fit (based on sock configuration selected) during testing via the Vicon method that produced a greater range but there is no data recorded for the exact sock configuration used on either test day. The elbow flex/ex case is harder to explain because only the photo method showed a significant difference. The first thought was that the proximity and size of the Vicon marker plates prevented the subject from achieving full joint range of motion by that method, but if that were the case, one would expect to see the photo method yielding greater ranges for both suited scenarios. For shoulder adduction/abduction, the difference is coming from data collected in the abduction direction (all adduction values within 2%), but without the original photos for reference, it is impossible to explain root cause any further. The leading idea, without better information, is that the suit elbow is able to abduct higher relative to the torso centerline than the shoulder element itself, thereby creating a larger range in Vicon data which measures shoulder abduction relative to the marker plate between the elbow and lower arm bearings and again taking greater advantage of the combined arm mobility elements. The complete mismatch on the ranges for hip ad/ab cannot be explained by any of the method reports, data, or the author's knowledge of the suit and experiment designs.

IV. Discussion

With respect to within suit condition comparisons, the data are shown as statistically equivalent with a 99% confidence interval, yet, in practical use, the data would be treated as extremely different. For example, if one were building a suit to mobility requirements generated from Vicon data, but doing in-house pre-delivery evaluations via photogrammetry, the above comparisons indicate that it would be extremely unlikely for the suit to actually meet its requirements when tested at delivery using Vicon. Thus, contractors fabricating suits to Vicon derived requirements must have access to the equipment and experienced system users.

Another limitation to comparing 2D photogrammetry and 3D Vicon methods for space suit joint ROM is the different base assumptions between the methods and the resulting limitations on data interpretation. Photogrammetry assumes that the plane of motion can be set orthogonal to the camera view and parallel to the static gridboard background. This set-up, however, is almost impossible to achieve for shoulder and hip designs. Accurate ROM is difficult to analyze for space suit shoulders because the joints are canted in toward both the sagittal and transverse planes. With these competing angles and limits of gravity, it is nearly impossible to align the plane of movement with the grid board and perpendicular to the camera view (DeWitt, 2007). This limitation is important to consider during overall mobility system design because the postures imposed by the bearing angles will reduce the force crew can impart to perform an activity even though they are theoretically working within the nominal strength ROM. The Vicon method uses equally limiting assumptions that presume, via location of the marker plates, that the mobility of the shoulder element of the suit is equivalent to the mobility of the lower arm element above the elbow joint and similarly that the mobility of the hip element is equivalent to the mobility of the lower leg element above the knee joint. These assumptions must be considered carefully because the definition of 'shoulder' as a space suit assembly component is complex with multiple mobility features required to emulate the three degrees of freedom in the human shoulder. For the MK-III and WEI suits, the shoulder component is comprised of three mobility features: a convoluted softgoods assembly bounded by a rotational bearing on each end. To perform the isolated adduction/abduction or lateral/medial sweeps, the shoulder component must rotate the scye bearing, rotate the upper arm bearing, and finally flex the convolute. When all of that joint programming is ignored, it seems that important subtleties between shoulder joint designs can easily be ignored. Additionally, these assumptions make cross method comparisons difficult because the origin for the angular data is not identical. Should shoulder mobility be defined as movement of the shoulder convolute alone for these sweeps and single out the scye bearing as the measure of flexion extension? That question cannot be solved by the data at hand, but should, in either case, should map back to the joint definitions for torque testing.

The final idea to consider based on the results comparisons is why the data for the overall group- that is minimum of the maximum values reported by each method- showed, on average, less difference between the digital and manual methods than the individual results. This result is not intuitive; one would generally assume that with less variables to confound the data, the within subject results would be much closer than the across subjects results. The information provided in the respective test reports does not provide information to explain this phenomenon, but it would appear that there is a broad range of expected values. If this vast range of variance does exist, it would be

impossible to compare results within subjects across suit conditions because there is no indication as to where within the range the results would fall.

V. Conclusions

While statistically the results of the two methodologies appear equivalent, for all practical purposes, they are vastly different. Based on this comparison, it seems that data must be compared only against data collected in the same manner. Comparing data within subjects does not necessarily improve the accuracy of comparisons across methods, across suit conditions, or within suit conditions. The range of expected values is entirely too variable to allow researchers to understand where in the span of accuracy they fall. Additionally, based on this comparison, one can conclude that statistical analysis is not the ideal means of comparing data; the percent differences provide a more practical understanding that directly relates to acceptability of space suit mobility system performance.

To improve the ability to cross compare suit data with future data collection methods and systems, researchers should spend time to understand the origin of the data to which new information will be compared. Every effort should be made to establish common segments of reference for angular measurements and common definitions of each suit component as related to human body segment (e.g. suit shoulder as compared to subject's shoulder). Additionally, effort should be spent to understand not only the independent mobility of the suit and the human but of the suit-human system. The suit-human system is forced to move with the programming of the suit but limited by human strength and flexibility in the suit induced postures. Without clear understanding of what interactions take place inside the suit as it is being articulated by the human, suited mobility data will continue to be clouded by noise in the data caused by the uncontrolled human-suit fit and interactions.

Acknowledgments

References

Abramov, I., Moiseyev, N., & Stoklitshy, A. (2004) Some problems of selection and evaluation of the Martian suit enclosure concept. *Acta Astronautica*, 57, 901-909.

Brock, H. (2010) Automated classification of trampoline motions based on inertial sensor input. (Unpublished masters thesis). Saarland University, Saarbrucken, Germany.

Coca, A., Williams, J., Roberge, R., & Powell, J. (2010) Effects of fire fighter protective ensembles on mobility performance. *Applied Ergonomics,* 41, 636-641.

DeWitt, J. & Jones, J. (2007) *Evaluation of the Hard Upper Torso Shoulder Harness*. (Report No. NASA/TP-2007-214751) retrieved from NASA Rechnical Reports Server: http://ntrs.nasa.gov/search.jsp?Ntx=mode matchallany|mode matchany&Ntk=All|Author-Name&N=0&Ntt=emu shoulder injury|Jones%20Jeff

Doriot, N. & Wang, X. (2006) Effects of age and gender on maximum voluntary range of motion of the upper body joints. *Ergonomics*. 49(3), 269-281.

England, S., Benson, E., & Rajulu, S. (2010) *Functional mobility testing quantification of functionally utilized mobility among unsuited and suited subjects*. (Report No. NASA/TP-2010-216122) Retrieved from NASA technical Reports Server: http://ntrs.nasa.gov/search.jsp?R=20100025770&hterms=sudhakar+rajulu&qs=Ntx%3Dmode%2520matchany%26 Ntk%3DAuthor-Name%26Ns%3DLoaded-Date%7C1%26N%3D0%26Ntt%3Dsudhakar%2520rajulu

Great Northern Technologies (2006, March) Leighton Flexometer. Retrieved from http://www.gntech.net/leighton/

Huck, J., Maganga, O., & Kim, Y. (1997) Protective overalls: evaluation of garment design and fit. *International Journal of Clothing Science and Technology*, 9(1), 45-61.

Jones, R.L. (1966) *Evaluation and comparison of three space suit assemblies.* (Report No. NASA TN D-3482) Retrieved from NASA Technical Reports Server: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19660022897_1966022897.pdf

Thomas, K. & McMann, J. (2006) *US Spacesuits.* New York, NY: Praxis

Ross, A. (2000) *Advanced space suit isolated joint mobility test for the space suit comparative technology evaluation test*. JSC-39522 (CTSD-ADV-387)

Ross, A., Kosomo J., Janoiko, B., & Eppler, D. (2004). *Desert Research and Technology Study 2003 Trip report/ICES Paper.* (Report No. JSC-CN-8455) Retrieved from NASA Technical Reports Server: http://ntrs.nasa.gov/search.jsp?R=20100042197&hterms=amy+ross+amy+ross+amy+ross&qs=Ntx%3Dmode%2520matchallany%7Cmode%2520matchall%26Ntk%3DAll%7CAuthor-Name%26Ns%3DLoaded-Date%7C1%26N%3D0%26Ntt%3Damy%2520ross%7Camy%2520ross

URS Corporation (1974) Development of an EVA systems cost model. Volume 1: Design guides synopsis – EVA equipment final report. NASA-CR-141634.