Evaluating Suit Fit using Performance Degradation

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The Mark III planetary technology demonstrator space suit can be tailored to an individual by swapping the modular components of the suit, such as the arms, legs, and gloves, as well as adding or removing sizing inserts in key areas. A method was sought to identify the transition from an ideal suit fit to a bad fit and how to quantify this breakdown using a metric of mobility-based human performance data. To this end, the degradation of the range of motion of the elbow and wrist of the suit as a function of suit sizing modifications was investigated to attempt to improve suit fit.

The sizing range tested spanned optimal and poor fit and was adjusted incrementally in order to compare each joint angle across five different sizing configurations. Suited range of motion data were collected using a motion capture system for nine isolated and functional tasks utilizing the elbow and wrist joints. A total of four subjects were tested with motions involving both arms simultaneously as well as the right arm by itself.

Findings indicated that no single joint drives the performance of the arm as a function of suit size; instead it is based on the interaction of multiple joints along a limb. To determine a size adjustment range where an individual can operate the suit at an acceptable level, a performance detriment limit was set. This user-selected limit reveals the task-dependent tolerance of the suit fit around optimal size. For example, the isolated joint motion indicated that the suit can deviate from optimal by as little as -0.6 in to -2.6 in before experiencing a 10% performance drop in the wrist or elbow joint. The study identified a preliminary method to quantify the impact of size on performance and developed a new way to gauge tolerances around optimal size.

Nomenclature

ROM	=	Range of Motion
UA	=	Upper Arm
LA	=	Lower Arm

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I. Introduction

There exists a gap in the current knowledgebase regarding space suit fit and how it impacts performance. Current sizing configurations allow for multiple sizes of suit components as well as sizing inserts to tailor the fit of the suit to an individual. It is unknown at what point an ideal fit transforms into a bad fit and how to quantify this breakdown. The questions this study seeks to address are: Can the designers and evaluators of space suits identify the point of departure whereby a change in suit fit causes a detriment of mobility-based physical performance? Subsequently, can this knowledge be applied to suit sizing options, suit size improvement, and eventually the suit design?

There are many places for sizing adjustment within the suit; however as a starting point this study attempts to identify and evaluate the suit fit characteristics that inhibit elbow range of motion (ROM) as well as the secondary aspect of wrist range of motion. This data will address knowledge gaps in the area of human-suit interfaces and provide a foundation for future analytical aids in the development of space suit designs.

The methods in this study focused on changes in elbow and wrist mobility due to incremental suit sizing modifications. Unsuited motion data was collected as a baseline to gather isolated ROM (maximal motion) and functional ROM (task-based motion) information for the elbow and wrist joints. Suited data for the Advanced Space suit Technology Demonstrator (Mark III) was collected for the same tasks. During those suited tasks the sizing of the suited arm was incrementally adjusted within a range that included both optimum and poor fit.

II. Methods

A. Subjects

Subjects were selected based on their ability to adequately fit the Mark III suit and were cleared through the JSC Human Test Subject Facility. Four male subjects were selected for testing based on availability and experience with the suit. The male percentiles for critical arm measurements representing how the subjects fall within the HSIR population of potential users is provided in Table 1.[1] The range of anthropometry observed between the subjects was 5.4 cm for arm length (wrist-wall length), 2.8 cm for upper arm (acromion-radial length), 2.8 cm for forearm length (radial-stylion length), and 1.6 cm for hand length. Even though these subjects' measurement variations seem to be close, Table 1 shows the wide range of the values when represented as male percentiles.

Table 1. Subject Percentiles[1]

Subject Identifier	Wrist-Wall Length	Acromion-Radial Length	Radial-Stylion Length	Hand Length
1	77	19	78	43
2	96	29	33	25
3	57	2	16	47
4	77	3	31	82

B. Test Hardware

The Mark III space suit with composite brief, lightweight composite torso, and low-profile waist bearing was used for this test at a pressure of 4.3 psid. The Mark III was sized according to standard practices for each subject, and this configuration was used as their baseline 'optimal' fit of the suit. The fit check procedure for the Mark III details the arm component and sizing ring lengths for sizing purposes in Appendix C of Ref. 2.[2] Sizing rings are cylindrical inserts that can be added or removed at key points of the suit arms and legs in order to lengthen or shorten them. The sizing values were used as the means for calculating the change in length of the arms due to swapping out components during the sizing configuration changes. The location of the sizing rings relative to the rest of the suit are visually illustrated in Fig. 1. Range of motion (ROM) data was collected using a Vicon optimal motion capture system (Vicon, Oxford, UK). Each subject was instrumented with a set of 12 retroreflective markers: four on the upper arm below the bearing, four on the lower arm above the bearing, and four on the hand/wrist.

Table 2. Mark III Arm Sizing

Arm Component	Length (cm (in))
Xshort	22.9 (9.0)
Short	26.4 (10.4)
Medium	28.6 (11.25)
Long	31.0 (12.19)
Sizing Ring	**Length (cm (in))**
Upper Arm -01	0.8 (0.304)
Upper Arm -02	1.5 (0.604)
Lower Arm -06	0.8 (0.304)
Lower Arm -07	1.5 (0.604)

C. Tasks

In addition to basic isolated joint motions, subjects also performed functional tasks. The isolated elbow flexion/extension is a simple arm curl about the elbow joint. The isolated wrist flexion/extension is movement of the hand in a patting motion, where the hand rotates back and forth in the direction of the palm and back of the hand. The ulnar/radial deviation is movement of the hand in a chopping motion. Fig. 2 illustrates the functional tasks that were performed for data collection. Functional tasks were based on common fit check tasks, motions common to suited performance, or motions that would test the limits of elbow/wrist mobility. All tasks were performed with three repetitions for each trial. Each test subject was coached in the proper performance and protocols for each of the test conditions. The tasks were performed sequentially first with the right arm only and then with both arms simultaneously, with the exception of Hammering which was right arm only. For the majority of tasks, the subject in the Mark III suit was locked into the suit stand, to minimize the effects of fatigue during testing by providing weight relief of the pressurized suit. For the last trial, Touch Points on Body, the suit was disengaged from the suit stand in order to allow the subject to reach the hip.

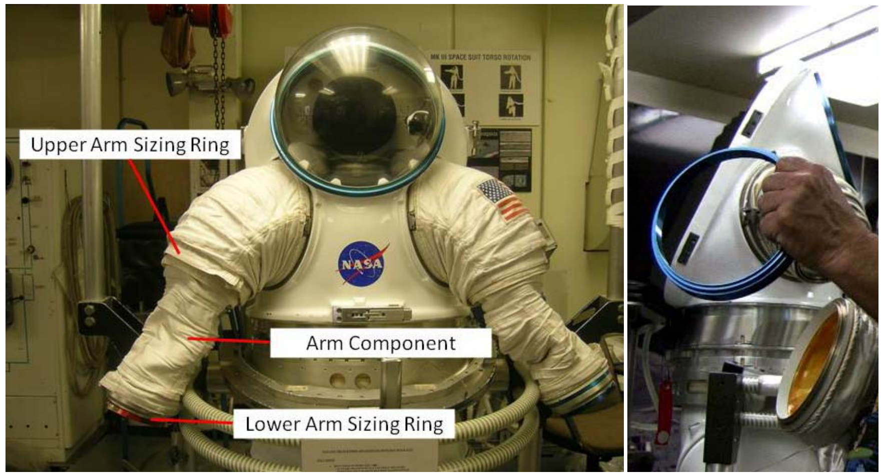
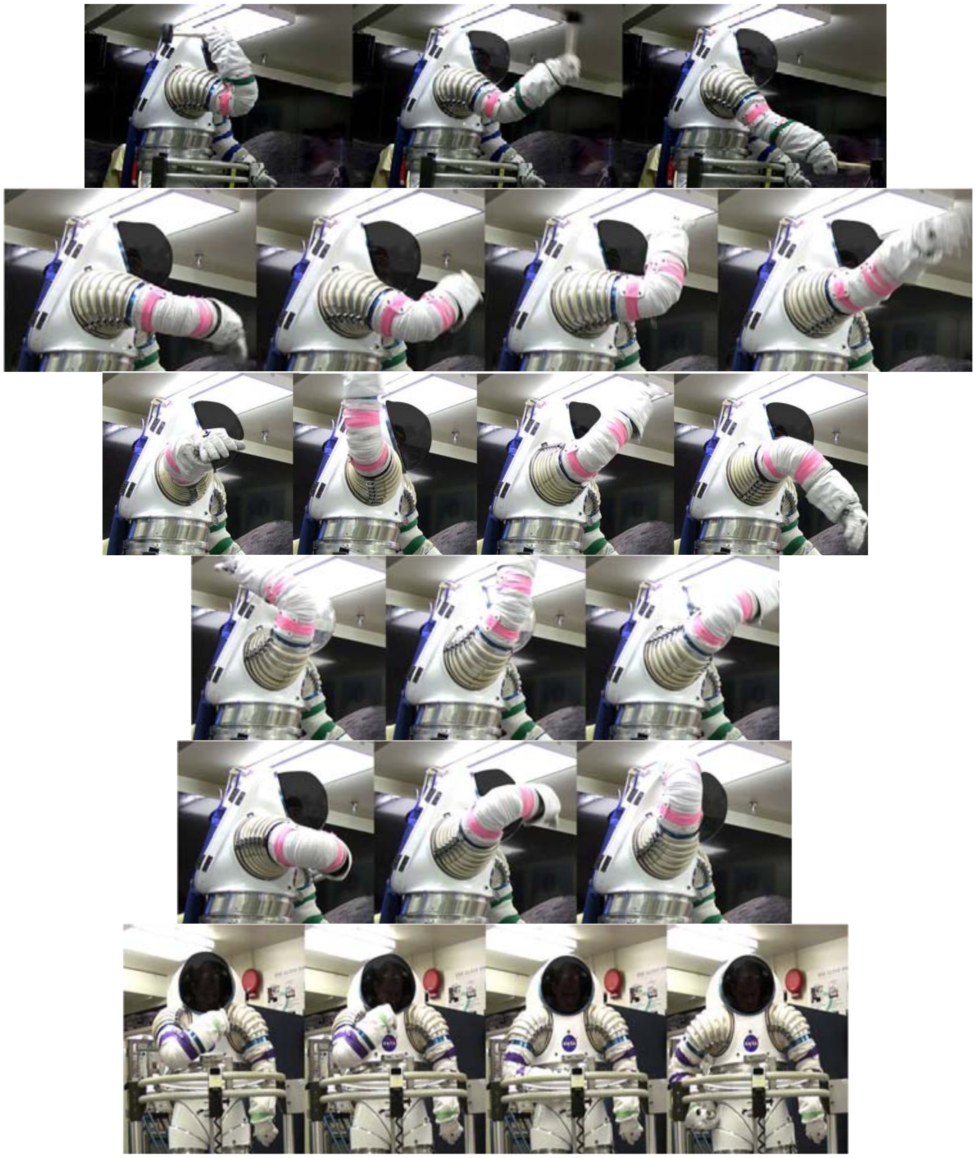


Figure 1. Location of Specific Mark III Suit Parts (left) and a Close-up of a Sizing Ring (right)

The Hammering task consisted of the subject grasping a rubber mallet pointed down and away from the body, and snapping the elbow back toward their shoulder and down again in a simulated hammering motion. The subjects also brought the wrist into the movement, mostly ulnar/radial deviation (Fig. 2-A) due to the positioning of the hand on the hammer. The Forward Sweep motion consisted of the subject placing their arms in front of their body, arms parallel to the floor and flexing and extending their elbow while holding their shoulder motion as steady as possible, in an attempt to maximize the motion of the elbow (Fig. 2-B). The Side Sweep was identical to the forward sweep, except the arms were initially abducted away from the body to create a T-shape (Fig. 2-C). Similarly, the Overhead Sweep was performed with the arms held above the head (Fig. 2-D). The sweeps were broken into the three separate motions in order to minimize the effects of the shoulder rotating and twisting the position and causing unforeseen effects as a result. The Visor Open/Close task was a simulated opening of a helmet visor, by placing the hand at the helmet neck ring location under the chin and tracing the curve of the helmet until the top of the head is reached (Fig. 2-E). The Touch Points on the Body consisted of the subject sequentially touching their shoulder, chest at the level of the bust, approximate bellybutton, and side of hip (Fig. 2-F).



A Hammering

B Arm Forward Sweep

C Arm Side Sweep

D Arm Overhead Sweep

E Visor Open/Close Reach

F Touch Points on Body

Figure 2. Example of Tasks Performed During the Test

D. Sizing Configuration Changes

The suit configuration was changed from the optimal sizing configuration by both lengthening and shortening the arms. The optimal sizing configuration was considered to be the default configuration taken from the subject's fit check procedure. The arms were lengthened for two sizing configurations and shortened for two sizing configurations, resulting in a total of 5 different sizing configurations to be tested (Table 3). Whether the arms were initially lengthened or shortened was heavily dependent on the optimal sizing configuration.

There are three ways to change the arm sizing configuration: by switching out the arm component (softgoods), the upper arm sizing ring (UA), and the lower arm sizing ring (LA). There are four different sizes of arm softgoods: extra-short (Xshort), short, medium, and long and two thicknesses of sizing rings for both the upper and lower arms (Table 2). For testing, only one sizing ring in each size was available for both arms, thus a maximum of two rings could be stacked for each sizing location, one each for the upper and lower arms.

In general, the sizing configurations attempted to initially create a dramatic size difference of an inch or more compared to the optimal size, either through addition/removal of sizing rings or swapping out the suit arm component for a different size. The next sizing configuration was influenced by the initial change by assessing the comfort of the subject and placement of the hand inside the glove, deciding whether to further increase the

Table 3. Sizing Configuration Changes by Subject

	Subject Number	1	2	3	4
Optimal	**UA Ring (in)**	-	-	0.304	-
	Arm Comp (in)	Medium (11.25)	Xshort (9.0)	Short (10.4)	Short (10.4)
	LA Ring (in)	-	0.908	0.304	0.604
	Total Length (in)	**11.25**	**9.908**	**11.008**	**11.004**
Short	**UA Ring (in)**	-	-	-	0.604
	Arm Comp (in)	Short (10.4)	Xshort (9.0)	Short (10.4)	Xshort (9.0)
	LA Ring (in)	-	0.304	-	0.304
	Total Length (in)	**10.4**	**9.304**	**10.4**	**9.908**
Shortest	**UA Ring (in)**	0.604	-	-	-
	Arm Comp (in)	Xshort (9.0)	Xshort (9.0)	Xshort (9.0)	Xshort (9.0)
	LA Ring (in)	0.304	-	-	-
	Total Length (in)	**9.908**	**9**	**9**	**9**
Long	**UA Ring (in)**	0.604	0.908	-	-
	Arm Comp (in)	Medium (11.25)	Xshort (9.0)	Medium (11.25)	Medium (11.25)
	LA Ring (in)	-	0.908	-	-
	Total Length (in)	**11.854**	**10.816**	**11.25**	**11.25**
Longest	**UA Ring (in)**	0.604	0.908	0.604	0.604
	Arm Comp (in)	Medium (11.25)	Short (10.4)	Medium (11.25)	Medium (11.25)
	LA Ring (in)	0.604	0.908	0.604	0.304
	Total Length (in)	**12.458**	**12.216**	**12.458**	**12.158**

difference from optimal or to reduce it by choosing a size in between at that point in time. Some sizing configuration changes were limited by the available sizes, specifically for Subject 2, whose optimal size was an Xshort arm component and two lower arm sizing rings. Since no smaller softgoods were available, the only shortening that could be performed was to remove the sizing ring(s), resulting in a very small change from optimal for both shorter lengths.

E. Data Analysis

Once the data collection session was complete, the Vicon motion capture data was reconstructed, labeled, and run through a custom set of MATLAB and Vicon Bodybuilder scripts to determine the elbow and wrist angles. The specific angles examined in the analyses were the elbow flexion/extension, wrist flexion/extension, and wrist ulnar/radial deviation. Wrist rotation (pronation and supination) was excluded because it is controlled mainly through the wrist bearing rotation of the suit causing a different motion in comparison to unsuited. In addition, the tasks examined in the analysis were not applicable to wrist rotation. The majority of the functional ROM tasks did not involve an analysis of the wrist angles, since the motions were primarily elbow-specific.

The range between the peak maximum and minimum angle values was calculated to determine the total ROM for each trial. The ROM value was then normalized as a percentage of the unsuited isolated ROM trial in order to place the data in context across subjects. The peak maximum or minimum values could not be compared directly because the marker locations were adjusted every sizing configuration, changing the baseline angles. This ROM data was then analyzed in relation to the optimal suit configuration ROM of each subject as defined by the fit check. To distinguish between different arm configurations within a subject, each sizing scheme (optimal, smaller, larger) was given an ID for easy reference. The ID for the optimal size configuration was taken as a baseline value of zero, with the configuration changes being indicated by a negative number (shortened arm) or positive number (lengthened arm), with higher numbers indicating a greater change from optimal.

Since the differences in sizing between the arm components and sizing rings cannot inherently be kept consistent for each subject, the differences in ROM between Person A and Person B cannot directly be compared since the length changes are different, but overall the ROM as a function of the change from baseline was examined across all subjects to evaluate the effects of fit on performance.

III. Results

The motion capture data for each task was examined for each subject for each size configuration. The ROM as a percentage of unsuited ROM was used as the primary method for comparing and contrasting the results across tasks and between subjects.

A. Optimal Suit Fit

The ROM at the optimal size configuration was evaluated to compare the percent difference from unsuited ROM across the various tasks (Table 4). The suit reduced the elbow flexion/extension ROM by an average of 26% across all tasks in comparison to unsuited, ranging from 4% to 47% for individual subjects. The wrist flexion/extension ROM was reduced from unsuited by an overall average of 19% ranging from 9% to 24% for individual subjects. The wrist ulnar/radial deviation ROM varied by subject, ranging from a reduction of mobility by 45% to an increase of 29% for individual subjects in comparison to unsuited. In general there was a greater reduction in mobility in the functional ROM tasks in comparison to the isolated joint ROM as evaluated against the baseline unsuited ROM.

Table 4. ROM for the Optimal Size Configuration in Comparison to Unsuited

Subject Identifier	1	2	3	4	Average
Elbow Flexion/Extension ROM (%unsuited)					
Isolated Elbow Flex/Ext	74	81	78	96	**82**
Hammer	66	72	82	89	**77**
Fwd Sweep	55	105	71	79	**77**
Side Sweep	61	96	85	92	**84**
Overhead Sweep	74	85	69	74	**76**
Visor Reach	69	44	71	53	**59**
Touch Points on Body	62	59	68	64	**63**
Wrist Flexion/Extension ROM (%unsuited)					
Isolated Wrist Flex/Ext	77	81	91	76	**81**
Wrist Ulnar/Radial Deviation ROM (%unsuited)					
Isolated Wrist Ulnar/Radial Dev.	129	93	124	86	**108**
Hammering	107	55	92	48	**75**

B. Isolated ROM Results as a Function of Fit (Unilateral)

The ROM for the isolated joint motions was examined for each subject across size configurations (Figure 3). The optimal ROM was assigned the baseline size configuration ID of zero. Since the sizing changes are relative to optimal fit configurations, lengthening the suit falls on the positive portion of the graph and shortening is on the negative portion of the graph. The sizes are classified as *shortest*, *short*, *optimal*, *long*, and *longest* configurations for the purpose of this paper.

The isolated elbow flexion/extension ROM (Figure 3-top) for Subject 2, 3, and 4 dramatically increased from the lowest ROM value in the *shortest* configuration to just above the optimal ROM value for the *short* configuration. This behavior was not reflected in Subject 1. When the suit arm was lengthened, Subjects 2 and 3 exhibited a drop in ROM in the *long* configuration before increasing for the *longest* configuration. In contrast, Subjects 1 and 4 continued to increase past optimal for the *long* configuration, but Subject 4 decreased moving into the *longest* configuration. Overall, the elbow flexion/extension of the suit was lower than unsuited (<100%) for all subjects, with the exception of one configuration (*long*) for Subject 4.

The isolated wrist flexion/extension ROM (Figure 3-middle) for the shorter configurations did not show a consistent trend. Subject 3 increases approaching *optimal*, Subject 2 had a higher ROM in comparison to *optimal* and an absolute maximum at the *short* configuration, Subject 1 remained relatively unchanged approaching *optimal*, and Subject 4 had a low ROM before rising sharply for *optimal*. When the suit arm was lengthened, all subjects exhibited a decrease in wrist ROM in comparison to *optimal* sizing, some more sharply than others. Overall, the wrist flexion/extension of the suit was lower than unsuited (<100%) for all subjects.

The effects of the sizing configuration on isolated wrist ulnar/radial deviation ROM varied by subject (Figure 3-bottom). The wrist ROM for Subjects 1 and 4 increased from the *short* to *optimal* size configurations while for Subject 3, it decreased. In the case of Subject 2, the wrist ROM was at first smaller than *optimal* in the *shortest* configuration and increases until it was larger than optimal in the *short* configuration. When the suit arm was lengthened (positive X-axis), Subjects 1, 2, and 3 exhibited an increase as the suit was lengthened in comparison to *optimal* fit. In contrast, the ROM for Subject 4 initially decreased from *optimal* in the *long* configuration and then increased as the suit was lengthened to the *longest* configuration, but still remained lower than *optimal*. Overall, the wrist ulnar/radial deviation of the suit was higher than unsuited (>100%) for Subjects 1 and 3 and partially higher for Subject 2 for the majority of data points.

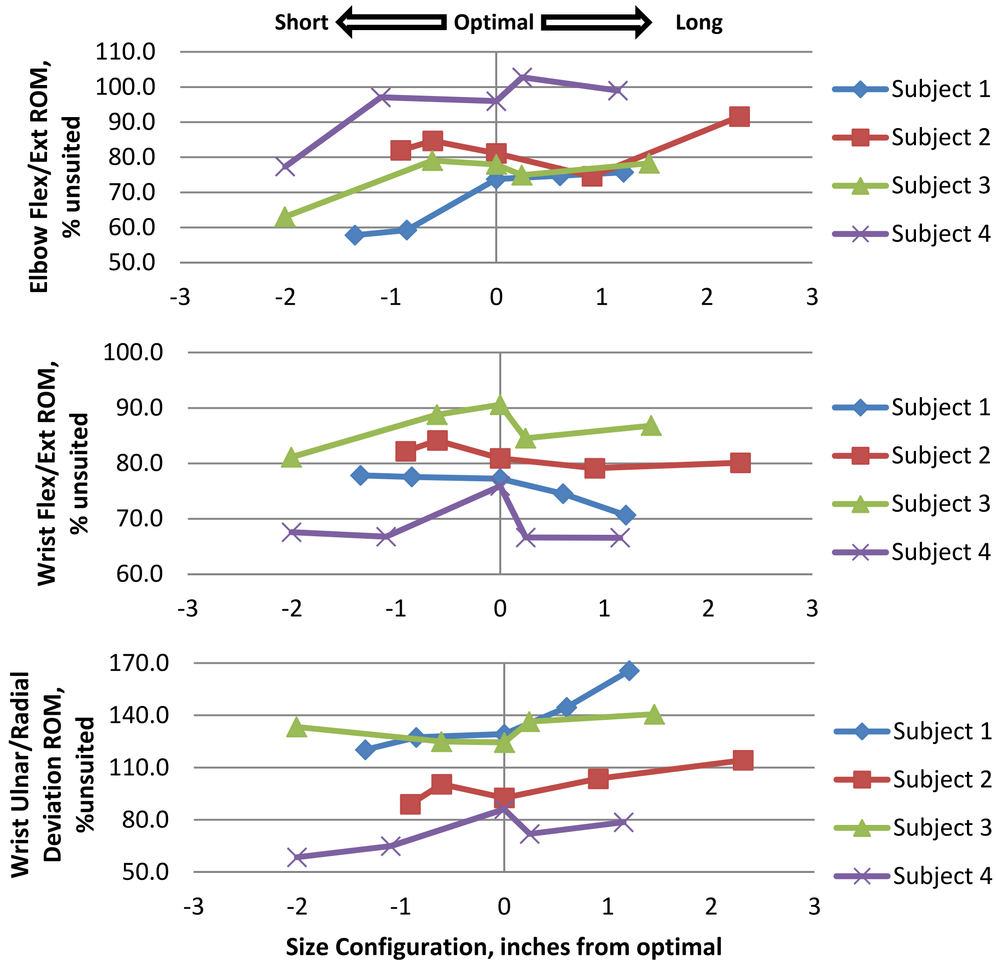


Figure 3. Isolated ROM by Subject as a Function of Size Configuration

C. Functional ROM Results as a Function of Fit (Unilateral)

It was determined through analysis that both a repeatable motion for subjects and maximization of the joint ROM of interest were required to observe any consistency across size configurations between subjects. The functional tasks, with the exception of hammering, failed in one or both of these goals. The arm sweeps (forward, side, and overhead) were focused on the elbow flexion/extension ROM. The sweep motions were inconsistent between each size configuration change; the subjects had been instructed to move freely while trying to reach to the very limits of their motion. The instructions should have been adjusted to adhere to a more standardized motion to achieve consistency between the different trials. Thus the sweep results did not yield any discernable consistent data between subjects and were discarded. The Visor Open/Close Reach task focused solely on the elbow flexion/extension ROM. Unfortunately, this task did not maximize the elbow joint ROM, in fact, the majority of subjects held their elbow rigid while using the shoulder to complete the motion. It was simply not an appropriate functional task for the test. Similarly, the Touch Points task did not maximize the elbow joint as hoped, the shoulder was the primary joint involved in completing the motion. Thus both the Visor Open/Close Reach and the Touch Points tasks were discarded for the analysis.

This study was exploratory, thus tasks were included which ultimately did not show a consistent pattern in ROM change with size adjustments. Since a part of this study was to determine what particular functional tasks could be used as fit benchmarking tools, it was not required that every task show a discernable change in ROM with suit fit.

1. Hammering

Similar to the isolated ROM results, the hammering ROM was examined for each subject across size configurations (Figure 4). The functional hammering task analysis focused on two joint motions performed simultaneously: the elbow flexion/extension (Figure 4-top) and the wrist ulnar/radial deviation (Figure 4-bottom). For the elbow flexion/extension in the shorter configurations, Subjects 2, 3, and 4 decreased dramatically from an absolute (Subjects 3 and 4) and relative (Subject 2) peak at the *optimal* size configuration. Subject 1 did decrease from *optimal* during shortening, but had a relative maximum in the *shortest* size configuration. For the longer size configurations, Subjects 2, 3, and 4 decreased for the *long* configuration and increased again in the *longest* configuration. In contrast, Subject 1 ROM increased as the length increased after the *optimal* size configuration. Overall, the elbow flexion/extension of the suit was lower than unsuited (<100%) for all subjects.

For the wrist ulnar/radial deviation, all subjects had the absolute peak ROM located at the *long* size configuration, with a decrease in ROM for the *longest* size configuration. For the shorter configurations, Subjects 3 and 4 had a minor relative peak in the *short* configuration with the ROM reduced slightly in the *shortest* size configuration. Subject 1 generally declined from *optimal* in ROM as the suit is shortened, whereas Subject 2 decreased slightly and increased above *optimal* in the *shortest* configuration. Overall, the wrist ulnar/radial deviation of the suit was higher than unsuited (>100%) for Subjects 1 and 3, and lower than unsuited for Subjects 2 and 4.

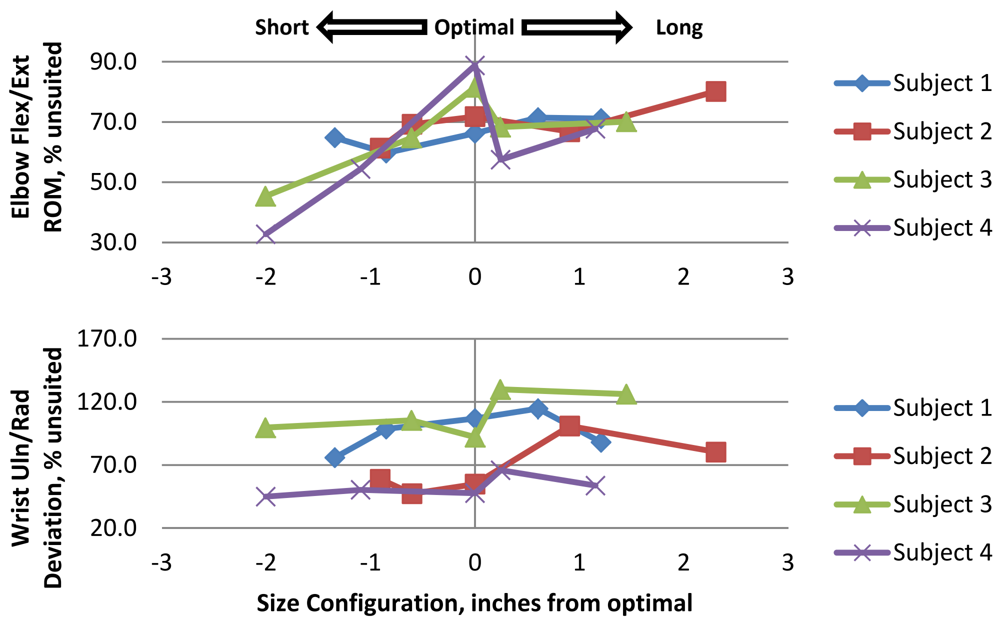


Figure 4. Hammering ROM by Subject as a Function of Size Configuration

IV. Discussion

A. Hypothesis of Suit Fit

Ideally, for any given range of motion, the suit fit would be tied directly to performance for any given joint of interest. It was originally theorized that the suit fit of the arm would be primarily linked to the elbow mobility, with wrist mobility playing a minor role in the overall performance of the arm relative to fit. In this regard, it was hypothesized that an *optimal* fit would have the *best* (highest) elbow ROM, with the *shortest* configuration having the *worst* (lowest) elbow ROM. The *longest* size configuration (termed the *worse* case) would see a decrement to elbow ROM relative to optimal but not to the extent of the reduction at the *shortest* configuration. This hypothesis was based on an earlier ABF study on clothing fit and size.[3] It was also hypothesized that trends in wrist ROM values would be similar to the elbow ROM, if any impact of fit on performance was observed.

The logic behind the hypothesis is that the shorter configurations would restrict mobility due to impingement of the suit on the body and improper location of the elbow joint whereas the longer configurations would restrict mobility to a lesser degree due to 'bad' fit. This section examines how the results of the study compare and contrast against this original hypothesis. Due to the low number of subjects and deviations between subjects, the data is presented and summarized in terms of general trends exhibited by multiple subjects.

B. Effect of Optimal Suit Fit on Performance

The effect of the suit causes an immediate detriment on elbow and wrist performance, even at optimal fit as observed in Table 4. Both the elbow and wrist flexion/extension ROM incurred a 19 to 26% detriment in ROM on average. If ROM is reduced by nearly 20% just by putting on an optimally sized suit, the next question is how much more of a detriment on top of that is acceptable due to poor suit fit?

C. Isolated Elbow Flexion/Extension

Elbow flexion/extension is one possible identifier of the impact of suit fit on performance (Figure 3-top). For the isolated task, in general, the data shows an increase and then reduction in mobility relative to *optimal* as the suit gets shorter for three out of four subjects. Similarly, there is an increase in mobility relative to *optimal* fit as the suit is lengthened to its *longest* configuration for three out of four subjects.

For the shorter size configuration conditions, there is a strange trend with three of the subjects (Subjects 2, 3, and 4), where a peak (2 absolute, 1 relative) ROM lies at a point other than the optimal fit, specifically the *short* sizing configuration. Using the previously stated hypothesis, the optimal fit should also yield the *best* or highest peak elbow ROM, since it was thought that the elbow motion is the primary driver of arm performance. This would indicate that the isolated elbow flexion/extension is not the primary driver of suit fit and there is another mechanism behind the relationship between fit and performance. However, since the shortened arm ROM is fairly consistent between three of the subjects the elbow flexion/extension ROM may play a role in the overall schema but cannot be the sole predictor of fit on performance.

In addition to the observation that the optimal fit is not the *best* elbow flexion/extension ROM value, the original hypothesis is also not supported by the longer size configurations, which do not reduce the elbow ROM relative to the optimal configuration, i.e. the longer sizing is not the *worse* condition observed in the data.

D. Isolated Wrist Flexion/Extension

Wrist flexion/extension is a possible indicator of suit fit on performance (Figure 3-middle). In general, the isolated data is variable in the shorter size configurations, either decreasing or remaining the same relative to *optimal* fit for all subjects. For the longer size configurations all subjects experienced a decrease in isolated wrist ROM in comparison to *optimal*.

With this particular task, while the lengthened arm effect is fairly consistent between subjects, the shortened arm effect is not, however this makes sense given the functionality of the suit. If the suit is shortened, there are two options for hand placement in the glove. The first is the hand placement should remain the same or similar to optimal fit and the second option is where the glove would jam against the fingertips or finger saddle points, potentially causing discomfort. In the case of the former, the wrist and associated ROM should remain fairly similar to optimal. The latter option would result in a reduction in ROM due to reluctance to put strain on the existing pressure points of the hands. The consistency of the lengthened arm effect is based on the fact that lengthening the arm should displace the hand from the glove, causing a shift in the suit's wrist breakpoint from the ideal location on the human body. Based on these results, wrist flexion/extension is a strong candidate for prediction of fit on performance for the longer suit configurations.

The isolated wrist flexion/extension results somewhat support the original hypothesis in that in some subjects the optimal fit is the *best* wrist ROM value. However the shorter size configurations are not the *worst* ROM relative to optimal for three out of four subjects; the longer size configurations are in fact the *worst.* Thus, the original hypothesis is not supported by the wrist flexion/extension results.

E. Isolated Wrist Ulnar/Radial Deviation

Wrist ulnar/radial deviation is another possible factor that would indicate how performance is impacted by suit fit (Figure 3-bottom). In general, as the suit is shortened, the isolated ROM data is reduced with respect to *optimal*, especially in the shortest configuration for three out of four subjects. With the longer configurations there is an increase in wrist ROM in comparison to *optimal* for three out of four subjects.

With this particular task, the trends observed in the shortened and lengthened arm are fairly logical given functionality of the suit. Similar to wrist flexion/extension, there are two options for hand placement in the glove if the suit is shortened, hand placement remains the same or the glove jams against the fingertips and saddle points of the hand. In the case of the former, the wrist and associated ROM should remain fairly similar to optimal and the latter option would result in a reduction in ROM due to reluctance to put strain on the existing pressure points of the hands. The consistency of the lengthened arm data is somewhat counterintuitive. If the wrist ulnar/radial deviation is similar to that of wrist flexion/extension, then the ROM should decrease as it lengthens because the lengthening the arm should displace the hand from the glove, causing a shift in the suit's wrist breakpoint from the ideal location on the human body, but instead it increases. A further analysis revealed the origin of the increase in ulnar/radiation is due to a suit effect; the shifting of the joint center of rotation from the actual location. The root cause of this shift is most likely due to the interaction of the soft goods versus hard good interactions of the suit and person. Based on these results, the wrist ulnar/radial ROM is of potential use for prediction of fit on performance.

The isolated wrist ulnar/radiation results do not support the original hypothesis in any way, with the exception that *shortest* size configurations are the *worst* ROM relative to optimal.

F. Hammering

The hammering task (Figure 4) is the only task that provided the opportunity to examine a two-joint simultaneous motion. In general, the hammering task elbow flexion/extension ROM peaks at the *optimal* fit size (2 absolute, 1 relative peak) and drops for both the *long* and *short* size configurations. For the wrist ulnar/radial deviation, the ROM for the shorter configurations and *optimal* fit are at a lower value, dramatically increasing to peak at the *long* size configuration. It is also surprising just how steep the elbow ROM decreases as it moves away from optimal for Subjects 3 and 4, dropping over 10% and 30% respectively within one size of the optimal fit. Similarly, the absolute peak wrist ROM at the transition from *long* size configuration to *optimal* results in an average difference of 27% in wrist ulnar/radial deviation, ranging from 8% to 46% across subjects.

There are two separate effects witnessed in the hammering data, one when the suit is shortened and the other when lengthened. At the *optimal* size configuration it appears that the hammering motion is primarily a mix of elbow and wrist, the elbow exhibiting between 60% to 80% of unsuited ROM while the wrist ranges from 40% to 100% ROM relative to unsuited performance. When the suit is shortened both wrist and elbow ROM are at a low point, indicating restricted mobility performance. This is logical since the shorter suit size is anticipated to cause this effect. When the suit is lengthened one step up to the *long* configuration, the elbow ROM drops while the wrist increases relative to optimal for all subjects, indicating that in order to produce the same hammering motion, the subjects are increasing the use of the wrist to produce the same hammer strike instead of relying on the elbow for the same effect. This might indicate a multi joint strategy where if one joint is impacted by fit, other joints compensate for the loss.

The functional hammering task results support the original hypothesis in the elbow ROM only. Specifically, the optimal fit is the *best* elbow ROM value for 3 out of 4 subjects (2 absolute peaks and 1 relative), the shorter size configurations are the *worst* ROM relative to optimal for all subjects, and the longer size configurations have a reduced ROM (*worse* condition) relative to optimal for 2 out of 4 subjects. However the original hypothesis is not supported in any way by the wrist ulnar/radial deviation ROM.

G. Summary and Modified Hypothesis

For reference for the rest of the analysis, a summary of the observed effects of fit on performance is provided in Table 5. These trends have been generalized from the points discussed in the previous sections and are relative to the optimal fit point within each task. Only one task supported the original hypothesis in full, thus a different approach to the interpretation of results must be determined.

The modified hypothesis proposed is that as the suit arm is shortened, there are observed restrictions in arm mobility across all measured joint angles. When the suit is lengthened, the response is variable across the joint angles observed. Ultimately, the lengthened arm will be driven by functionality of the hand and placement within the glove. Thus sizing is a careful balance between the shortened arm mobility restrictions and the correct positioning of the hand in the glove.

Table 5. Summary of Observed General Effects Relative to Optimal Fit

Task	As Suit Arm shortens:	As Suit Arm lengthens:
Isolated Elbow Flex/Ext	ROM decreases (after mild increase)	ROM increases
Isolated Wrist Flex/Ext	Same or Decreasing ROM	ROM decreases
Isolated Wrist Ulnar/Radial Dev	Same or Decreasing ROM	ROM increases
Hammering Elbow Flex/Ext	ROM decreases	ROM decreases
Hammering Wrist Ulnar/Radial Dev	Same or Decreasing ROM	ROM increases

The analysis concerning the hammering task and the observations that no single angle drives the performance as a function of suit fit leads to the potential concept that suit fit is linked to a combination of multiple joints and angles, not just a single one. The interactions between two or more joint angles may yield an improved method for quantifying performance against suit fit.

The idea that the impact to performance can span across multiple joints does increase the complexity of the analysis, yet at this point there is no evidence that one angle measurement is representative of the relationship between suit fit and arm mobility.

H. Using Performance to Determine Sizing Changes

If suit fit is linked to a combination of multiple joints and angles how then can the point of departure be identified whereby a change in suit size causes a detriment of mobility? Ultimately, the end goal is to find out just how much of a difference is allowed from optimal fit given an acceptable performance detriment allowance. For example, since the suit already reduces elbow and wrist performance by approximately 20%, then is a total 30% performance detriment acceptable for an off nominal suit fit, 40%, 50%? At what point does that detriment occur in the sizing configuration is changed from optimal?

If a 10% performance detriment in arm mobility for an off-nominal sizing is selected as the maximum impact on performance allowed for any given joint in addition to the baseline optimal suited performance detriment, then the issue becomes calculating what shortening effects cause a 10% performance drop, and finding the smallest change in sizing of all the angles involved. As a hypothetical example, if a 10% performance decrease in ROM was selected, shortening of the suit to meet a 10% decline of each ROM could result in a 1 inch sizing change using the elbow flexion/extension ROM, 0.5 inches using the wrist flexion/extension ROM, and 0.7 inches using the wrist ulnar/radial deviation ROM data. In this case, 0.5 inches would be the minimum the suit could be shortened before witnessing a 10% drop in performance in any joint's ROM. Based on the modified hypothesis, the performance concern is focused only on the shortening of the suit arms, since the lengthened arm will be driven by functionality of the hand and placement within the glove.

With only four subjects, only two shorter and two longer data points, and wide differences observed in the behavior of the ROM graphs in some instances, averaging the data or creating trend lines in the graphs would not yield usable results for most cases. Thus, the prediction of performance detriment as a function in fit presented in this paper is not a straightforward answer and relies on the existing data in each graph. For a certain value of performance detriment from unsuited, this difference from the optimal ROM value was determined by finding the intersection for the value on the Y-axis for both the shorter and longer size configurations (See Example in Figure 5: 5% Drop in Mobility). If the value exceeded the existing graph, the line at that configuration was extended using the standard equation of a line, if possible (See Example in Figure 5: 15% Drop in Mobility).

The resulting data calculated using a 10% detriment and a 20% detriment from this method is provided in Table 6 for the isolated joint tasks and the hammering tasks. Examination of the isolated joint data leads to the conclusion that the suit arm can be shortened across subjects ranging from 0.6 inches up to 2.6 inches before the subjects experience a 10% performance drop in the wrist or elbow joints across subjects. The range is similar for the functional hammering task; the suit arm can be shortened across subjects from 0.3 inches up to 3.2 inches before the subjects experience a 10% performance drop for those same respective joints across subjects. At a minimum, a 10% drop can occur between 0.3 and 0.9 inches of size reduction from optimal size for any

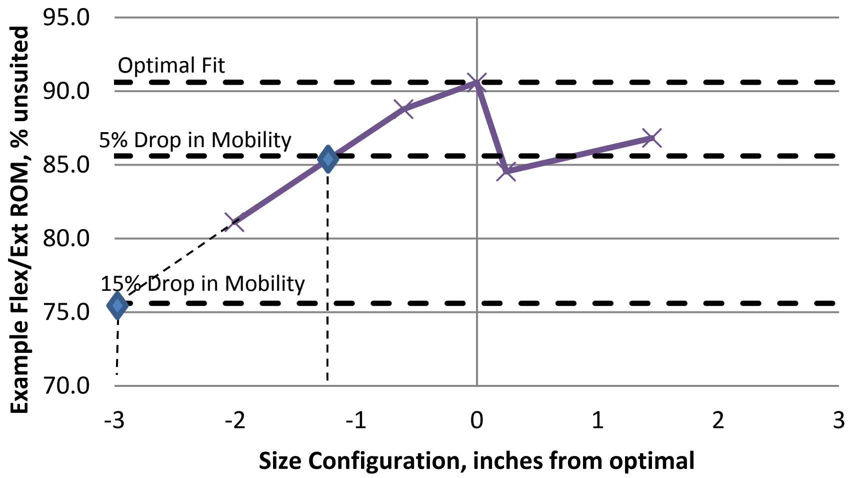


Figure 5. Example of Calculation to Determine Size Limit Range (5% and 15% selected for visualization only)

given joint and task. Likewise, a 20% drop can occur between 0.6 and 1.3 inches of shortening from optimal.

Essentially, the data illustrates how much adjustability in suit fit there can be before a drop in performance occurs. This data can then be translated into sizing information as a tolerance value from a design perspective. With the data from above, a 10% reduction in mobility was exhibited with 0.3 to 0.9 inches of shortening within the suit. In terms of a tolerance factor, that means that a suit design must be able to achieve sizing increments of 0.3 to 0.9 inches in order to fall within the acceptable performance detriment.

This study has shown the potential of quantifying suit fit based on performance, but the implementation and execution of this knowledge needs to be refined. For implementation, is a 10%, 20% or some other value acceptable to use across all joints? Or is a combination of performance detriments, such as a combination of 10% elbow and 20% wrist decline, more realistic? An acceptable performance detriment must first be selected and agreed upon, before the resulting suit sizing tolerance factor can be incorporatd into a design solution. Regarding execution of fit based on performance, only four subjects were tested in this study and no overarching trendline was discovered within the data. If enough sizing configuration points across more subjects could be tested, the data could be averaged and standardized to minimize the range of data observed in Table 6.

Table 6. Summary of Sizing Limit Calculations

10% Drop						
Subject	**Elbow Flex/Ext (in)**	**Wrist Flex/Ext (in)**	**Wrist Uln/Rad Dev. (in)**	**Hammer Elbow Flex/Ext (in)**	**Hammer Wrist Uln/Rad Dev. (in)**	**Minimum Size Change (in)**
1	0.6	-	1.4	-	0.9	0.6
2	2.1	2.6	1.1	0.9	-	0.9
3	1.6	2.1	-	0.4	-	0.4
4	1.6	-	0.5	0.3	3.2	0.3
20% Drop						
Subject	**Elbow Flex/Ext (in)**	**Wrist Flex/Ext (in)**	**Wrist Uln/Rad Dev. (in)**	**Hammer Elbow Flex/Ext (in)**	**Hammer Wrist Uln/Rad Dev. (in)**	**Minimum Size Change (in)**
1	2.7	-	2.1	-	1.1	1.1
2	3.3	4.2	1.3	1.3	-	1.3
3	2.5	3.9	-	0.8	-	0.8
4	2.1	-	1.0	0.6	4.9	0.6

I. Limitations, Assumptions, and Constraints

No female subjects were tested and the male subjects tested were above average in arm length. The behavior of smaller sized individuals may differ from what was observed in the test. Similarly, limited suit sizing reduced the potential combinations available for sizing changes, which once again may influence the results observed in the test. The reduced amount of subjects and the narrow size range complicates the summation and interpretation of the data analysis. In addition, the shoulder mobility was not included within this analysis. The shoulder ROM could potentially be affected by the sizing configuration changes to a higher degree in comparison to elbow or wrist ROM, yet due to both the complex nature of the shoulder motion within the suit as well as the inability to determine shoulder position relative to the suit the shoulder was excluded from this exploratory analysis.

There is an inherent amount of error when using motion capture systems due to noise in the calculated location of the marker centroid. Filtering algorithms used during the analysis process remove any large noise spikes. Typically this error is $< \pm 3°$ degrees.

Other effects not captured may influence the data, for instance the shoulder placement of each subject within the Mark III Hard Upper Torso of each subject or even the mobility of each subject within the suit.

V. Conclusion

The results of this study indicate that ROM can be used to quantify at what stage suit fit causes a detriment in performance. Unfortunately, it is not due to a single joint angle, but the interaction of multiple joints along a limb. It was determined that wearing the suit reduces the ROM in the elbow and wrist by nearly 20% in comparison to unsuited.The functionality of the arm is dependent on the lengthening of the suit due to the hand placement and operation within the glove. The study found that the arm mobility is further impacted by shortening the suit arm.

Thus sizing is a careful balance between the mobility restrictions associated with a shortened arm and the correct positioning of the hand in the glove. Using a selected performance detriment from shortening the suited arm, acceptable suit fit sizing increments can be determined as applicable to design. In this manner, a cost effective solution regarding the number and range of sizing increments can be determined by examination of the suited subjects changes in ROM.

The study was able to identify a preliminary method to quantify the impact of size on performance using a selected performance detriment to calculate the impact on fit. Thus, there exists a means of quantifying suit fit based on performance.

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