HUMAN POTENTIAL OF APPLYING STATIC FORCE AS MEASURED BY GRIP STRENGTH: VALIDATION OF ROHMERT'S FORMULA

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Introduction

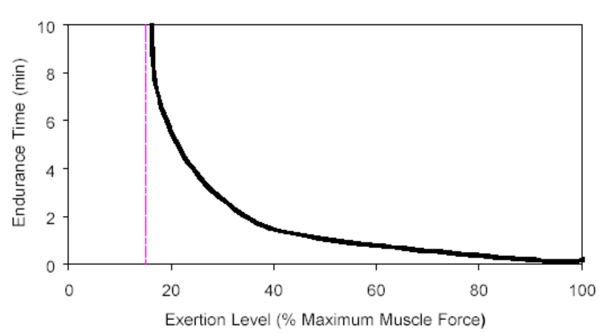
Static force involves a constant contraction of the muscles without movement. Sustained muscle contraction can restrict blood flow which normally provides oxygen to the muscles. Thus, static force results in little nourishment supplied to the muscles, and reduces the metabolic waste removed from the muscles (Konz and Johnson, 2000). This build up of metabolic waste, and lack of oxygen result in the onset of muscle fatigue, which can be described as the inability to continue exerting muscle effort (Kroemer, Kroemer and Kroemer-Elbert, 2001).

In 1960, Rohmert discovered a non-linear relation between one's ability to maintain a static force (the onset of fatigue) and the percent of one's maximum voluntary contraction (MVC) they are holding (Bloswick and Ellis, 1974). A formula was developed, which calculated time of endurance, based on the percentage of one's MVC they are trying to sustain.

$$T_{(sec)} = -90 + (126/P) - (36/P^2) + (6/P^3)$$

Where P is the decimal percentage of maximum force applied.

Charting this formula results in what has been referred to as Rohmert's curve.



This curve displays static muscle endurance in time, as a function of the percent of the MVC exerted. From this study, Rohmert deducted that 15% or less of MVC can be sustained indefinitely.

The value of this type of analysis is the ability to match equipment or system requirements to the efficiency of human abilities. If a worker's ability to maintain a force is predictable based on a MVC, equipment can be designed to function within these parameters.

More often than not though, work is performed under varying conditions, some of which can be replicated in laboratory settings. Protective gear or clothing is often worn in the work environment, and can potentially interfere with one's performance. Gloves specifically can increase friction, thus increase torque, but have been found to decrease grip strength up to 21% of non-glove use (Konz and Johnson, 2000).

In this study, we will attempt to validate Rohmert's formula, by comparing subjects' ability to maintain varying percentages of their MVC of grip strength, with the predicted time using Rohmert's formula. We will also investigate the effect of wearing work gloves on subjects' MVC.

Method

Experiment 1

There were two stages to this experiment. The first was to record subject's maximum grip strength. Various percentages of maximum grip strength were calculated for each subject. These percentages were then used in the second stage, which measured the subject's holding time for each of these percentages. This data will then be plotted against calculated estimates for holding times.

Subjects

Two subjects were used, both right handed male graduate students, aged 28 and 44. They had not had any previous experience with the measuring apparatus. They were experienced in using various hand tools. Subjects were not active weightlifters.

Apparatus

A stopwatch was used to calculate the time of completion for each trial. A Jamar Hydralic Hand Dynamometer, model 5030J1, was used to measure the hand grip strength. The handle adjusts to five grip positions, from 1 3/8 to 3 3/8 in. to accommodate various size hands. For our experiment, we positioned the gap at 1 7/8 in. At the top of the apparatus is a gauge facing away from the user, that displays the hand grip strength when the handles are clinched. This gauge displays in kilograms and pounds, our data uses kilograms.

A compact mirror was used so that the subject could view the gauge, and assess how he or she is holding up the percentage of force. The other pieces of equipment that we used were a lab table that was big enough for the subject to sit comfortable and be able to have enough space to concentrate on their maximum force, and a chair to sit on.

Definition of Variables

The independent variable manipulated for this experiment was the percentage of subject's maximum hand grip strength. Percentages from 30% to 90% in 10% increments were used, resulting in seven trials. The dependent variable measured was the length of time subjects could hold the various percentages of their maximum strength. The subject variables were kept to a minimum because we only had two subjects perform the experiment. The only subject difference measured was strength, but due to the nature of the experiment we weren't comparing strength between subjects. It was only used to calculate the maximum force for each subject.

Controls

We reduced the chance of fatigue, by having the subjects rest three minutes between each trial. We also randomized the trials so that the subject's arm and grip would not lose stamina. For instance, we did the 30% trial and then rather than going to the 40% trial, we went to the 90% trial, alternating between a small percentage and a large percentage. The subject did not know what percentage to expect next, nor did they know the calculated time for each trial. The subjects did not exercise between trials or sessions.

To get the most accurate readings from the apparatus, we eliminated the chance of the subject influencing the dynamometer by shaking or jerking the apparatus, by having the subject position the dynamometer resting upright on the table with their arm fully extended. We also prevented the grip from slipping on the handles, by wrapping a latex glove around the handle to promote a better grip. The serial number of the equipment was recorded, to ensure the same equipment was used for every trial and session.

Procedure

The procedure for this experiment had the subject sitting comfortable at the table. The subjects were given the dynamometer and was told to use it five times to become familiar with the apparatus.

The subject was handed a dynamometer and asked to place it on the table, upright in their right hand. The subject was told to extend their arm and to swiftly squeeze the handles, pulling them together, then immediately releasing. This procedure was done five times alternating between subjects, to get the average maximum force for each subject. Once that data was collected, the subjects were allowed to rest.

For the next part of the experiment, one experimenter calculated the different percentages of the subject's maximum strength.

Once the trials were prepared, the subject was told to place the dynamometer upright and with their arm fully extended, to hold the particular percentage of force for as long as they could. Before starting the procedure it was decided that the subject would indicate when they cannot hold the force anymore by saying, "I'm Done!." An experimenter sitting opposite the subject held the mirror, so the subject could view the gauge. Another experimenter timed the trial.

Once one trial with one subject was completed, roles were switched and the other subject was tested. This gave the previous subject a time to rest between the trials (approximately 3 minutes). This procedure alternated between the two subjects, until both had completed the entire sequence of trials.

Experimental Design

One variable, percentage of maximum force was manipulated, and one variable, holding time for that force was measured. Sequence of trials was varied to reduce fatigue and possible subject expectations. Subjects alternated trial runs, to allow rest periods between trials.

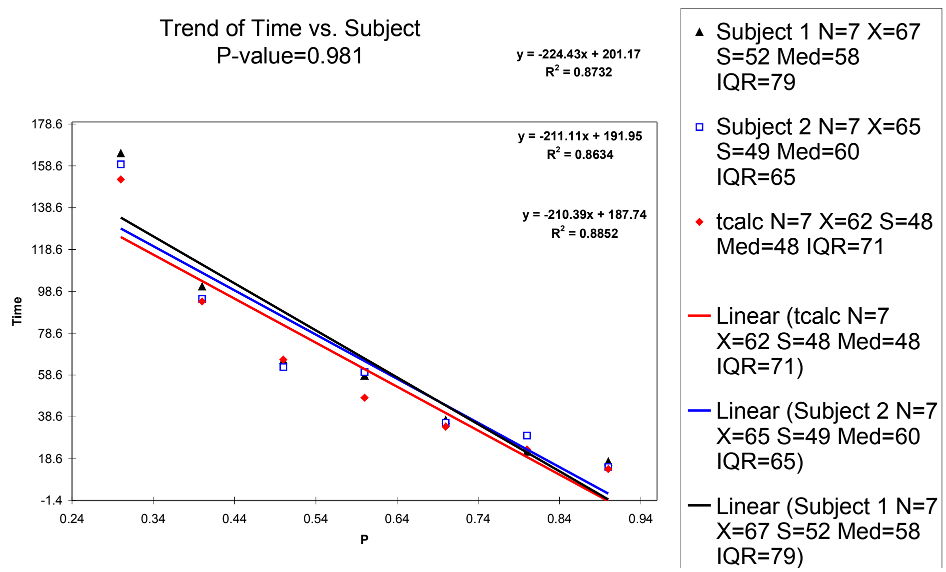
The trials were run in the following sequence:

Trial 1: 30%	Trial 5: 50%
Trial 2: 90%	Trial 6: 70%
Trial 3: 40%	Trial 7: 60%
Trial 4: 80%	

Results

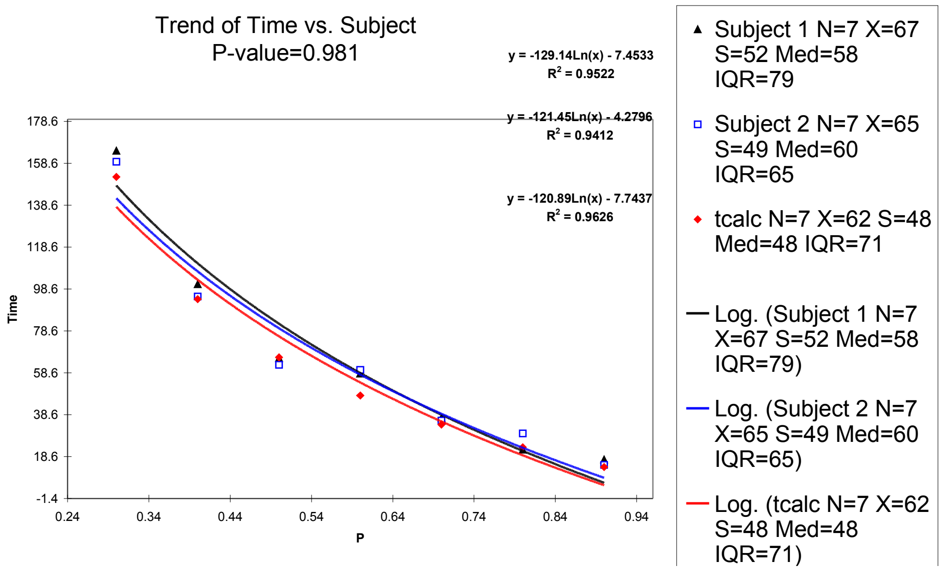
The data collected for Experiment 1 is displayed in Appendix 1. The data was plotted against four different regression models to test the linearity of the results.

Graph 1 shows the averaged data for subject 1 (triangles), averaged data for subject 2 (squares), and the calculated values from Rohmert's formula (circles) plotted on a linear regression model. Percentages of maximum strength held are on the y axis, and time (sec) are recorded on the x axis. The P-value is 0.981. The R^2 values for subject 1, subject 2 and calculated values are, 0.8732, 0.8634, and 0.8852.



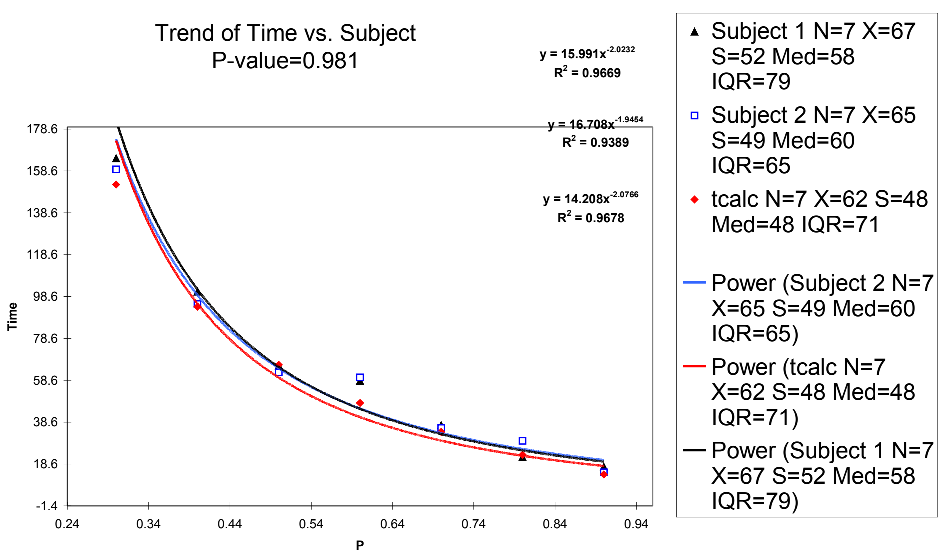
Graph 1: Linear regression model

Graph 2 shows the averaged data for subject 1 (triangles), averaged data for subject 2 (squares), and the calculated values from Rohmert's formula (circles) plotted on a logarithmic regression model. Percentages of maximum strength held are on the y axis, and time (sec) are recorded on the x axis. The P-value is 0.981. The R^2 values for subject 1, subject 2 and calculated values are, 0.9522, 0.9412, and 0.9626.



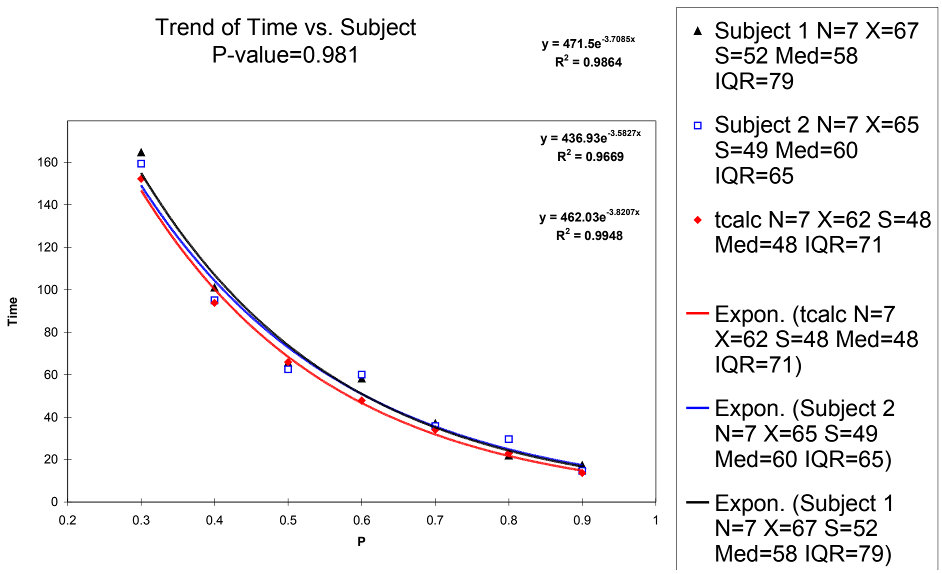
Graph 2: Logarithmic regression model

Graph 3 shows the averaged data for subject 1 (triangles), averaged data for subject 2 (squares), and the calculated values from Rohmert's formula (circles) plotted on a Power regression model. Percentages of maximum strength held are on the y axis, and time (sec) are recorded on the x axis. The P-value is 0.981. The R^2 values for subject 1, subject 2 and calculated values are, 0.9669, 0.9389, and 0.9678.



Graph 3: Power regression model

Graph 4 shows the averaged data for subject 1 (triangles), averaged data for subject 2 (squares), and the calculated values from Rohmert's formula (circles) plotted on a Exponential Regression Model. Percentages of maximum strength held are on the y axis, and time (sec) are recorded on the x axis. The P-value is 0.981. The R^2 values for subject 1, subject 2 and calculated values are, 0.9864, 0.9669, and 0.9948.



Graph 4: Exponential regression model.

Table 1 summarizes the R^2 values for each data set in each regression model plotted. Linear regression obtains the lowest overall R^2 value in every sample, indicating that a Linear Hypothesis is least supported by the data collected during the testing and by the calculated expectations. The exponential regression model provides the best fit.

Regression Method	**Calculated**	**Subject 1**	**Subject 2**
Exponential	0.9948	0.9864	0.9669
Power	0.9678	0.9669	0.9389
Logarithmic	0.9626	0.9522	0.9412
Linear	0.8852	0.8732	0.8634

Table 1: R^2 value comparison of different regression methods

Experiment 2

This experiment will test the effect of wearing a glove on subject's maximum grip strength. Average grip strength with and without a glove was recorded and will be compared to each other.

Subjects

Two subjects were used, both right handed graduate students. One subject was male, 23 years old and the other subject was female, 25 years old. They were not the same subjects that were used in Experiment 1. They had not had any previous experience with the dynamometer. They were experienced in using various hand tools. Subjects were not active weightlifters.

Apparatus

The same equipment as Experiment 1 was used for Experiment 2, the only additional equipment was a leather work/gardening glove. A stopwatch was not needed for this experiment.

Definition of Variables

The independent variable manipulated for this experiment was the use of the work glove when measuring maximum grip strength. The dependent variable measured was the maximum grip strength.

The subject variables were kept to a minimum because we only had two subjects perform the experiment. The only subject difference measured was strength, but due to the nature of the experiment we weren't comparing strength between subjects. It was only used to calculate the maximum force for each subject. Both were very similar in weight and strength.

Controls

We reduced the chance of fatigue, by having the subjects rest three minutes between each trial. We reduced the possible affect of fatigue on the data, by having the subjects alternate between glove, and non-glove trials, subject 1 starting without the glove, subject 2 starting with the glove, so if fatigue did occur, it would have been distributed between the variables. The subjects did not exercise between trials. The serial number of the equipment was recorded, to ensure the same equipment was used for every trial.

Procedure

The procedure for this experiment had the subject sitting comfortable at the table. The subjects were given the dynamometer and was told to use it five times to become familiar with the apparatus.

The subject was handed the dynamometer and asked to place it on the table, upright in their right hand. The subject was told to extend their arm and to swiftly squeeze the handles, pulling them together, then immediately releasing. Subject 1's first trial was without a glove, subject 2's first trial was with a glove. After each trial one experimenter read the dynamometer and recorded the data.

This procedure was alternated between subjects, allowing approximately 3 minutes rest between trials for each subject. There were 10 trials using the glove and 10 trials without using the glove, resulting in 20 trials, to calculate average grip strength, with and without wearing the glove.

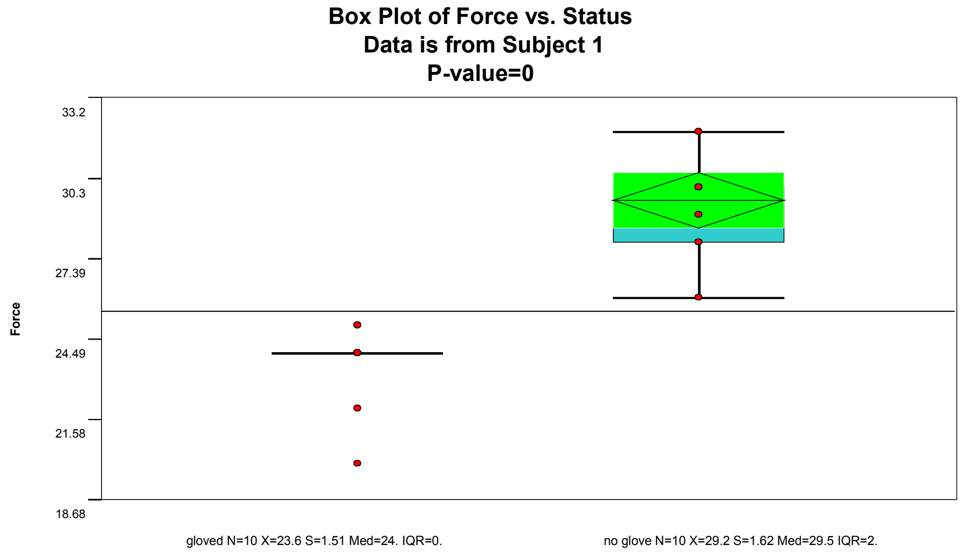
Experimental Design

One variable, wearing or not wearing of the glove was manipulated, and one variable, grip strength was measured. 20 trials were run, alternating between wearing and not wearing the glove, resulting in 10 trials for each variable. Subjects alternated trial runs, to allow rest periods between trials.

Results

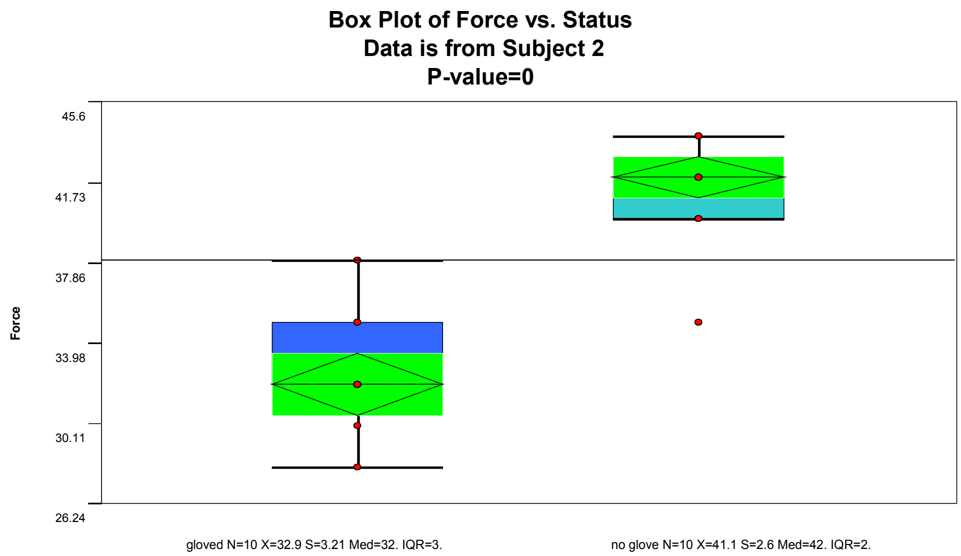
The data collected for Experiment 2 is displayed in Appendix 2. The data for each subject, with glove, and without glove was plotted in a box plots, displaying the differences in averages and the range of values recorded.

Graph 5 shows the maximum force applied on the apparatus with wearing glove on the left side, and maximum force applied on the apparatus without wearing glove on the right side for subject 1. The average maximum force with the glove is 29.2 kg, the average maximum force without the glove is 23.6, a difference of 80.82%. The P-value is 0.



Graph 5

Graph 6 shows the maximum force applied on the apparatus with wearing glove on the left side, and maximum force applied on the apparatus without wearing glove on the right side for subject 2. The average maximum force with the glove is 41.1 kg, the average maximum force without the glove is 32.9, a difference of 80.05%. The P-value is 0.



Graph 6

A summary of results for experiment 2 is displayed in Table 2, displays mean maximum force for subject 1 and subject 2, with and without glove, and the percentage difference.

	Mean Gloved Force (F_G)	**Mean Ungloved Force (F_U)**	**Ratio (F_G/F_U)**
Subject 1	23.6	29.2	80.82%
Subject 2	32.9	41.1	80.05%

Table 2: Comparison of gloved and ungloved forces in kg.

Discussion

Experiment 1

Maximum strength varies from individual to individual, but is there a relationship between percentages of that maximum strength to an elapsed time that would hold across individuals?

This concept has been the subject of confirmatory research in the past and was selected in the first experiment as a validation vehicle of Rhomert's curve, which hypothesizes that the relationship between percentage of maximum strength and time is non-linear.

To test this hypothesis, we studied the relationship between maximum strength and the time a static grip could be maintained at different percentages of that predetermined maximum strength. Our results demonstrate that when choosing a regression technique to represent the data; Linear regression is the least mathematically supported method of the four methods we applied. These results, by virtue of supporting non-linear regression over that of linear regression, support the Rhomert curve hypothesis: that the relationship is non-linear.

Since muscle fatigue is hypothesized to be involved with this lapse in sustainable time of maintaining a static grip (Kroemer, Kroemer and Kroemer-Elbert, 2001), high percentage trials were alternated with low percentage trials. There is a possibility that a gradual overall fatigue affected the subjects throughout the duration of the testing despite the resting times between tests. This gradual fatigue could explain the differences between the results obtained during this research and that of the calculated Rhomert curve.

Experiment 1 Limitations

Even though our results validate the Rhomert curve to a statistically valid level, some limitations should be pointed out. These limitations could allow future studies to consider additional data collection and obtain results which fell outside the scope of this work.

The experiment was conducted in a very relaxed environment with extraneous stimulus such as sound and motion outside of the control of the experimenters. These stimuli could have affected the experiment.

Due to time constraints and the validation tests that we were studying (two phenomena simultaneously) within this work; we limited ourselves to one completed battery of 0.3 - 0.9 strength testing per subject. A total of two subjects was used. Repeated testing of the same individual could provide mean times to compare to Rhomert's curve, but the effect of fatigue after a few trials of strength (>0.5 maximum) was apparent. To compensate for this potential effect, a second subject gathered the percentage of maximum strength measurements while the first subject rested. Two personnel were required to operate the apparatus, and during the first lab, one of the group members was absent, reducing the subjects available to two.

The experiment was limited to one design of apparatus. In future studies it would be possible to vary grip position, posture, or even apparatus grip design to provide results that take in variation of comfort or ergonomic advantage.

It is important to note that these findings may or may not hold across gender lines, out of convenience and time restriction, both subjects were male.

Experiment 1 Generalization/Conclusion

This experiment validated the hypothesis that percentage maximum strength and sustained static grip has a non-linear relationship. This conclusion can be applied in design of tools or operation technology where a force is a design consideration. In designs where substantive force is required to offset the possibility of accidental operation such as construction operation (e.g. jackhammers and cranes), hand clutches for machinery, and handbrake design for bicycles and motorcycles: the grip strength must be considered as a limitation of the operators and the entire spectrum of potential users must be considered if the force of sustained operation is substantial. In firearm, barcode gun, and other trigger-operated designs, applied time of operation is not sustained over prolonged duration; the minimum operation force can be applied for safety. An option for keeping high activation strength for potentially dangerous tools or devices would be a threshold initiation force and a lower sustained grip operation force, which would enable longer operation without sacrificing safety.

Experiment 2

In work that includes gripped tools, there is a potential for the use of protective gear to protect the user from either the equipment being used or the work that is being done such as in the case of gloved jackhammer operators. A consideration for a designer who is producing a gripped equipment is the interaction of the protective gear with the design.

Previous research (Konz and Johnson, 2000) has found a relationship between maximum grip strength and nature of operation (i.e. whether wearing gloves or not).

To test this hypothesis, we studied the effect between maximum grip strength under gloved and ungloved conditions. Our results provide two data sets which, when compared, can be used to 1) determine the presence of such an effect and 2) quantify an effect (if present). The results gathered by this team demonstrated a statistically significant difference between gloved and ungloved maximum strength trials. In magnitude, the difference is practically significant gloves reduced maximum strength by 19%

and 20% for the two subjects, similar to the 21% difference noted by Konz and Johnson. This concept warrants further study as its impact to design of tools is potentially great.

Experiment 2 Limitations

Even though results validate previous research (Konz and Johnson, 2000), there are limitations to the experiment that should be highlighted for those who wish to pursue future studies in this area.

Due to time constraints and convenience, we were limited to two subjects, and twenty trials split evenly between gloved and ungloved situations. Since all data was collected in one session, it is possible that fatigue could have contributed to the results. A plot of the data collected as a function of trial progression is inconclusive. Each subject had a positive trend through progression and a negative trend through progression, but none of the trends were particularly strong (all with $R^2 < 0.25$, three with $R^2 < 0.1$) (see chart 7). It is noted that both subjects were right hand dominant and the hand that possessed the negative trend was the dominant hand. It is also possible that testing the subjects at the end of a workday could have influenced the results.

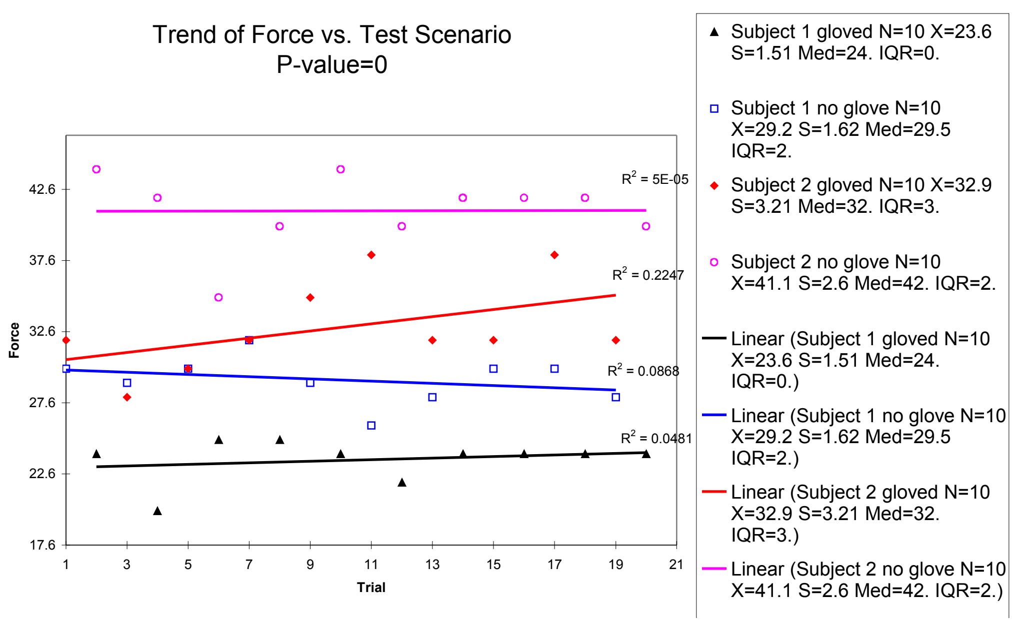


Chart 7.

The two subjects were of different genders that may or may not be representative of their respective populations.

The experiment was conducted in a very relaxed environment with extraneous stimulus such as sound and motion outside of the control of the experimenters. These stimuli could have affected the experiment.

In future studies, the time of data collection could be compressed or expanded to fully comprehend such effects as increasing fatigue. The number of subjects changed to better represent the population and grouping by gender to account for gender dependant results (if any). This experiment limited the type of glove to one, different glove types are put forward as suggested future exploration.

Experiment 2 Generalization / Conclusion

We validated the results of previous research (Konz and Johnson, 2000), and showed that there is a quantifiable effect on maximum strength in the presence of protective gloves. This conclusion can be applied to equipment design. If the usage of gripped equipment is expected to be solely in conjunction with protective gloves, the minimum operating force required would be lower than if the design did not allow for gloves. Construction equipment is often used with gloves, as is equipment prone to thermal effects such as smelting machinery. The operating environment that equipment is considered in the design phase, and this research indicates that the operator of the equipment is a consideration as well.

Appendix 1: Experiment 1 Data

Percent of Max Strength	T(sec) calc*	Subject 1 T(sec)	Subject 2 T(sec)
30%	152.2	164.4	159.3
40%	93.8	100.9	95.0
50%	66.0	65.6	62.5
60%	47.8	58.2	60.0
70%	34.0	37.1	35.8
80%	23.0	21.9	29.7
90%	13.7	17.3	14.7

* Calculated using Rohmert's Formula

Appendix 2: Experiment 2 Data

Trial		S1 Trial Type	S1 Force (kg)		S2 Trial Type	S2 Force (kg)
1		without glove	30		with glove	32
2		with glove	24		without glove	44
3		without glove	29		with glove	28
4		with glove	20		without glove	42
5		without glove	30		with glove	30
6		with glove	25		without glove	35
7		without glove	32		with glove	32
8		with glove	25		without glove	40
9		without glove	29		with glove	35
10		with glove	24		without glove	44
11		without glove	26		with glove	38
12		with glove	22		without glove	40
13		without glove	28		with glove	32
14		with glove	24		without glove	42
15		without glove	30		with glove	32
16		with glove	24		without glove	42
17		without glove	30		with glove	38
18		with glove	24		without glove	42
19		without glove	28		with glove	32
20		with glove	24		without glove	40

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