The effects of Force and Exertion Duration on Duty Cycle Time: Implications for Productivity, Human Factors and Ergonomics in Manufacturing and Service Industries, 2010, 20 (4), pp. 324-334 which has been published in final form at http://dx.doi.org/10.1002/hfm.20224

The effects of Force and Exertion Duration on Duty Cycle Time: Implications for Productivity

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Abstract

Ergonomics has positive effects on both physical health and productivity, but estimating productivity benefits is difficult at the task design/redesign stage. Rest allowance prediction models are not suitable for repetitive short cycle dynamic tasks and MTM techniques are limited in their suitability for considering ergonomics risk factors such as posture and force. The purpose of this study was to investigate the relationship between force and exertion duration on self selected duty cycle time and discomfort. Twenty one participants completed repetitive upper limb exertion treatments, each of duration ten minutes. Five levels of Force (10, 20, 40, 65 and 80% MVC) and Exertion period (1, 2, 4, 6.5 and 8 seconds) were investigated. The psychophysical adjustment method was used whereby participants self selected a work pace for the second half of each treatment. Duty cycle, derived from the self pace cycle time, was the measure of productivity effects in the experiment. ANOVA revealed a significant effect on duty cycle time for force, exertion period and the interaction (each $p<0.0001$). Friedmans test indicated a significant effect of force ($p<0.0001$) and exertion period ($p<0.0001$) on discomfort. Spearman's correlation analysis showed a strong correlation between discomfort and duty cycle time ($p<0.05$). Multiple regression analysis was used to develop a predictive model for duty cycle time based on force and exertion period, and this was a good fit to the data ($R^2 = 0.98$, $p<0.05$). Profiles were generated presenting zones of acceptable self selected duty cycle times based on force and exertion duration.

1. **Introduction**

Work is healthy. Actually, non-participation in work is unhealthy (Waddle and Burton, 2006). But work tasks vary in quality. Musculo Skeletal Disorders (MSDs) are a frequent repercussion of some badly designed tasks, and these are among the most common work-related health concerns of industrialised nations (Waters, 2004). Of the 7 million work related disorders reported across Europe in 1999 approximately half (52%) were MSDs (Eurostat, 2002). Vahtera et al. (1997) highlighted that industrial practices such as down sizing and work intensification which aim to improve productivity appear to be strongly associated with medically certified sick leave and the occurrence of MSDs. Work related postural pain and discomfort effects productivity in two ways. Through absenteeism where the worker is injured and not at work, and through presenteeism, when the worker is at work but has reduced capacity due to physical limitations (Meerding et al., 2005).

Vink (2006) stated that there is a need for a more proactive approach to ergonomics by emphasising positive conations of benefits due to interventions. For ergonomics interventions in repetitive work this is not easily achieved. MSD evaluation approaches can be used to estimate reduction (or increase) in risk likelihood for redesigned tasks, but simultaneous estimation of effects on time parameters of tasks is difficult. Some estimates can be made using MTM techniques but these are limited in considering detailed aspects of musculoskeletal loading.

Back in 1973 Rohmert reported on the negative view of engineers to recovery time in the ergonomic design of tasks. In modern industrial production systems time parameters of tasks remain of critical importance due to their inherent link with productivity (Wells et al., 2007). For work requiring a considerable labour input labour productivity is output per unit time. As such productivity is often related directly to cycle time, which comprises exertion period and rest time. In the workplace there are often different approaches by engineers and ergonomists; both manipulate time aspects of work to achieve different goals. In production workstation design, work-study and line balancing techniques are used to assign work tasks to workers based on a projected output. Engineers follow a cycle of optimisation which can increase biomechanical exposure, the magnitude of which can far exceed the reductions from ergonomic interventions (Wells et al., 2007).

Duty cycle time (%), the proportion between exertion and cycle time describes the non-rest component of work. Engineers aim to eliminate time wastage (some of which may be rest time) and intensify the time that is spent on tasks to improve output, while ergonomists aim to improve over-all health as well as improve productivity. But insufficient rest time is a well recognised risk factor for MSDs (Punnett and Wegman, 2004; Niosh 1997). A selection of rest recovery models are available in the literature (Rohmert 1973, Milner 1985, Rose et al. 1992, Byström and Fransson-Hall, 1994). But there are inconsistencies in their predictions (El ahrache and Imbeau, 2009). Moore and Wells (2005) and Mathiassen and Winkel (1992) expressed concerns about using models such as the rest allowance model of Rohmert (1973) in the design of short cycle jobs as the science behind the models were primarily based on endurance data from static exertions. Abu-Ali et al (1996) investigated the effects of physical risk factors on self selected duty times, a measure of productivity. They developed a predictive model for duty time but it was limited for forces in the range 25 to 50% MVC and times between 1 and 5 seconds. As only two levels of each independent variable were used it was not possible to test for curve linear effects, especially for force which most often has a curve linear relationship with strength and fatigue. Furthermore, their model did not include a parameter to capture the significant two-way interaction between force and exertion time.

The psychophysical approach has been used successfully in a number of studies to investigate relationships between MSD risk factors and in the setting of exposure limits. The approach involves participants making subjective judgements about their perceptions. The dependent variable is often either a rating of a perception magnitude, e.g. discomfort, or the adjustment of an exposure to an acceptable level, e.g. maximum acceptable work pace or force. For example, Khan et al. (2009) used discomfort ratings in the study of posture effects for forearm rotation combined with wrist flexion/extension for two levels of force. Others have used the psychophysical approach to determine work cycle parameters based on physical risk exposures. Snook and Ciriello (1991) used the psychophysical approach to design guideline tables of maximum acceptable weights and forces in the design of manual handling tasks. Snook et al. 1997 also used the approach to determine maximum acceptable forces for repetitive ulnar deviation of the wrist. Moore and Wells (2005) used the method to present psychophysically determined acceptable torques in a highly repetitive upper limb task with both cycle time and duty cycle time as factors.

Wells et al. (2007) identified the need for approaches which aid both technical experts (engineering) and ergonomists when designing production systems. The approach of the Abu-Ali et al. (1996) model of duty cycle time (albeit restricted in predictive use) is helpful in conveying to engineers the conditions where high levels of duty cycle times might be acceptable based on ergonomics criteria. The objective of the present study was to expand this approach by developing profiles of acceptable duty cycle time for a large range of forces and exertion durations typical in industrial tasks. These data can be used in the development of methods for both engineers and ergonomists to decide on acceptable time parameters for tasks.

2. Method

2.1 Purpose of the study

The purpose of this study was to investigate the hypothesis that there is an effect of force and exertion period on self selected Duty Cycle Time (DCT) and discomfort. The study also proposes to develop a predictive model with profiles for DCT indicating zones which are considered ergonomically acceptable for a simulated task.

2.2 Participants

Twenty one participants (12 females and 9 males) were involved in the study. Eighteen were right handed and three were left handed. The majority were students at the University. The mean age was 24.8 years (SD= 5.7), mean stature 1.73 meters (SD=0.11) and mean body mass 78.1 kg (SD=17.31). All participants were interviewed to ensure they had no history of MSDs. The University of Limerick Ethics committee approved the experimental procedure. Participants were paid €65 for performing the experiment.

2.3 Experiment Design

The experiment involved repetitive upper limb exertions at five levels of force (10, 20, 40, 65 and80% MVC) and five levels of duration of exertion (1,2,4,6.5 and 8 seconds). The combinations of 65 and 80% MVC with 6.5 and 8 second exertions were considered unsafe to test due to risk of injury, so the remaining combinations comprised twenty one treatments. Twenty one participants performed the treatments which were ordered according to a 21X21 Latin Square.

Force levels were based on categories in the Strain Index (Moore and Garg, 1995). In the Strain Index the lowest force category is <10% MVC and this was set to 10%, while the level ≥ 80% MVC was set at 80%. Pre-tests indicated that it was difficult for participants to perform repetitive treatments above 80% MVC reliably. For the first five minutes of each treatment the cycle time was set at 10 seconds. For minutes five through ten participants maintained the same exertion duration but adjusted the cycle time to increase or reduce rest time based on the perception of what they could perform for a full eight hour work day. Duty cycle time derived from self paced cycle time, and discomfort ratings at the end of each treatment were the dependent variables.

Percentage duty cycle time was calculated using exertion period and SPCT at 10 minutes as perAbu-Ali et al. (1996) and Moore and Wells (2005). Upper limb discomfort was recorded using a 100 mm Visual Analog Scale (VAS) on the computer interface. The VAS ranged from 0 (no discomfort) to 10 (extreme discomfort). This scale has been used in a number of experiments previously in the University (Carey and Gallwey, 2002 & 2005; O’Sullivan and Gallwey 2002; Mukhopadhyay et al., 2007).

2.4 Apparatus

2.4.1 Experimental rig

A steel fixture with positioning straps and a grip strength meter was fabricated in house. An electronic, digital grip force dynamometer (MIE Medical Research Ltd Digital Analyser, UK) was interfaced with the computer via RS232. Strap restrains were used to ensure the participant’s forearm remained in a fixed position during testing. The entire fixture was attached to an adjustable height table and an adjustable height chair was used to adjust the upper arm posture. The main body of the fixture, where the forearm rested, was padded with a thin layer of cushioning to avoid elevated contact stresses (Figure 1).

Figure 1 about here

2.4.2 Data acquisition and computer interface

Virtual Instruments (VIs) were written using G code in Labview (V8.2) to control the experiment. A series of separate VIis were coded for each part of the experiment and loaded dynamically into memory. The force dynamometer signals were configured within Labview and readings were displayed in real time on the visual display unit for the VIs (Figure 2).

Figure 2 About here

2.4.3 Procedure

Participants were interviewed under the guidelines of the University of Limerick Ethics committee to ensure they fully read the experiment information sheet and that it was clear what the experiment involved. It was also explained that if at any time they wished to terminate the experiment they were free to do so. Participants also completed a questionnaire to ensure that they had no pre-existing musculoskeletal conditions in the preceding twelve months.

The participant was seated and the table height adjusted so that the fixture height was at elbow level. The forearm was positioned and strapped in place with the centre of the wrist inline with the hinge of the fixture and the dynamometer aligned with the centre line of the participant’s forearm. Maximum grip strength was recorded in line with the Cadwell regime with the wrist neutral, forearm prone 90°, elbow flexed 90°, and the upper arm abducted at 0°.

The participant was instructed to perform the task treatment for five minutes at the prescribed levels, according to the computer interface. After five minutes they were to self select a pace by adjusting the up or down arrow on the cycle time dialog in the interface with a mouse. The self selected pace was to reflect what they perceived they could perform for a full eight hour day.

Before the commencement of the first treatment the participant preformed a trial run for 3 minutes so as to gain familiarity with the task. Each of the 21 treatments were preloaded on the computer for each participant number and presented by the Labview software. Treatments lasted 10 minutes with 5 minutes break for recovery, or until the participant felt no discomfort. The experiment lasted approximately 6 hours with a half and hour break after 3 hours. Hence, the experiment was representative of ¾ of a typical 8 hour shift.

3.Results

3.1 Statistical Analysis

DCT was a percentage so the square root arcsin transformation was applied to it. The resultant data were normally distributed and the data did not violate the assumption for equality of variance (Levene's test, $p = 0.45$) so parametric tests were permissible. The discomfort data were considerably skewed and it was not possible to apply a suitable transformation to normalise it, so non-parametric tests were used in this case.

To test for independence between the treatment levels, paired sample t-tests were conducted on the DCT data while Friedmans test was conducted on the discomfort data using combination as the grouping variable. The results for both were significant ($p<0.05$) indicating that the combinations were independent.

3.2 Duty Cycle Time

Analysis of Variance was performed on the DCT data for the main effects (force and exertion duration) and the two way interactions. It was not possible to test all interaction effects due to limited degrees of freedom. The results (Table 1) indicate that Force ($p<0.001$), Exertion ($p<0.0001$) and participant each had a significant effect on DCT. There were also significant two-way interactions for Force and Exertion ($p<0.0001$), Participant and Force ($p<0.0001$) and Participant and Exertion ($p<0.001$).

Tukey post hoc tests were subsequently preformed on the DCT data and the results are shown in Table 2. For Force four subsets were identified with 10%, 20% and 40% MVC each separate, and 65% and 80% MVC together. For Exertion duration each level was grouped separately.

Table 1 about here

Table 2 about here

Mean and Standard Deviations for the raw and transformed DCT data at 10 minutes are shown in Table 3 for each of the Force and Exertion duration combinations. The lowest DCT value was for the combination Exertion 1 and Force 80% MVC (9.58%), whereas the highest DCT value was for the combination Exertion 8 seconds and Force 10% MVC (77.25%). In general, it can be observed that as the as the level of Force increased at all levels of Exertion Period there was a decrease in Duty Cycle Time.

Average DCT data for Force versus Exertion are shown in Figure 3. There was a general decrease in DCT for higher levels of Force, as identified in the post-hoc analysis. The data also illustrate higher DCT values for longer Exertion which was also highlighted in the post-hoc analysis where there were five separate subsets for Exertion.

Table 3 About here

Figure 3 About here

3.3 Discomfort

Friedmans tests indicated there was a significant difference in discomfort for Force ($p<0.0001$) and Exertion Period ($p<0.0001$). The average Discomfort data for Force versus Exertion Period are shown in Figure 4. The data indicate a general increase in Discomfort for higher levels of both Force and Exertion duration. Spearman’s correlation analysis also revealed a significant correlation between discomfort and DCT ($p<0.05$).

de Looze et al. (2005) in a study of acceptable work pace for simulated assembly of electric shavers, used ratings of 3 (on a 0-10 scale with same anchors as in this study) as the criterion for intervention to adjust cycle times. This action limit applied to the data in the present study indicated combinations of Force and Exertion duration for which discomfort may be acceptable. By this, all levels of Exertion duration were deemed acceptable for 10 and 20% MVC. For 40 and 65% MVC only the 1 and 2 second Exertion duration combinations were deemed acceptable, while for 80% MVC only 1 second was acceptable.

Figure 4 About here

3.5 Modelling Duty Cycle Time, Force and Exertion Period

Average DCT values were calculated for the Force and Exertion Period combinations. Multiple linear regression was used to predict DCT % for Force and Exertion duration (Equation 1). ANOVA revealed a significant effect for the interaction between Force and Exertion so this was also included in the model. Curve fitting indicated a log fit to the data for Force so the natural log of MVC (%) was used in the model. The model was highly significant and a good fit to the data ($p<0.0001$, R^2 0.98). Each of the predictor variables were also significant in the model (Exertion $p<0.0001$, Force $p<0.047$, interaction $p<0.007$). Values for both force and exertion period were inserted into the model to generate the DCT profile (Figure 5). In addition, acceptable and unacceptable combinations of Force and Exertion, based on the discomfort action limit in Figure 4 are delineated with the addition of a DCT action limit. Combinations of treatments below the action limit satisfy two conditions; they are psychophysically selected self selected pace conditions that also induced discomfort below the de Looze et al. (2005) level of 3.

Equation 1 about here

Figure 5 About here

4. Discussion

4.1 Force and Duty Cycle Time

Forceful exertions are a significant risk factor for MSDs (Kumar, 2004). In this study higher levels of force resulted in higher discomfort and lower duty cycle times. The general effects of force on discomfort are inline with many other studies. Lin et al. (1997) investigated a metric for quantifying biomechanical stress in repetitive motions and exertions using two levels of force (15 and 45N). For all combinations investigated the higher levels of force were found to increase discomfort by between 50 and 100%. Moore and Wells, (2005) investigated the effect of cycle time and duty cycle time on psychophysically determined acceptable levels of force in a highly repetitive task. It was found that as rest time for each of the combinations tested decreased so too did the level of torque selected. Abu-Ali et al. (1996) found a large decrease in duty cycle time (almost 50% in some cases) when the level of force exerted increased form 25 to 50% MVC. This is inline with the findings from this study where force had a significant negative effect on productivity (DCT). This is expected as higher forces require more rest time (Rohmert, 1973). But rest recovery models are not accurate enough to predict rest needs in repetitive short cycle repetitive tasks so hence are not suitable for predicting productivity effects.

4.2 Exertion Period and Duty Cycle Time

Exertion duration and DCT are closely linked; the former is the work time, and the latter a percentage of the cycle time which the work represents. This study found that longer exertion periods resulted in higher levels of DCT. Abu-Ali et al. (1996) also found higher levels of DCT at longer exertion periods. As for force this is expected; longer duration exertions required longer rest times. Data on work:rest regime effects indicate that the relationship between exertion duration and rest duration is not independent of exertion duration. That is, as the duration of exertion increases, there is a need for increasingly larger proportional increases in rest time (Van Dieen et al. 1998). This is evident in the present study in the significant two-way interaction in the ANOVA and also the significant effect for the same term in the DCT regression model.

4.3 Discomfort

Poor ergonomic working conditions promote operator discomfort and therefore limit operator performance (Vink et al., 2006). Analysis of the data highlighted that both force and exertion period had a highly significant effect on both discomfort and productivity ($p<0.0001$). Kuijt-Evers et al. (2007) investigated the relationship between discomfort and performance in hand tool design. It was found that when a hand tool caused discomfort one could not continue to work at high pace or indeed without a break. Such cases were associated with feelings of discomfort and related to reduction in productivity. The high negative correlation between discomfort and DCT in this study is in agreement with this. An earlier study by Finneran and O'Sullivan (2009) using structural equation modelling found that discomfort was a mediating variable in the relationship between force, posture and self paced cycle time (and DCT). These findings prove that by reducing discomfort productivity in self paced work is expected to improve.

4.3 Modelling Productivity

The regression model explained a large amount of the variation in the DCT data (R^2 =0.98). Sample values were entered into the the simpler model of Abu-Ali et al. (1996) for comparison (Table 4). DCT predictions were similar for higher levels of force (50% MVC) but at lower levels (25% MVC) there were reasonable differences in the predictions. There are several reasons why this may have occurred. Firstly, the method varied between the two studies. In this study participants worked at a set cycle time for 5 minutes and then altered their cycle time based on the discomfort they were experiencing. In the Abu-Ali et al. study participants altered their cycle time from the start of the experiment for the first 30 minutes and then maintained this for the remaining 10 minutes. The duration of treatments also was different. For this study it was 10 minutes compared with 40 minutes for Abu-Ali et al. But the present study had a larger sample size (21 versus 12).

The proposed model extends the work of Abu-Ali et al. (1996) by using more levels, a larger range of values, and by using the log of force. Also, the model includes a parameter for the interaction effect.

Table 4 About here.

4.3. Study Limitations

This study tested treatments for ten minutes per combination. While it is preferable and desirable to perform such experiments for longer durations of time, the primary objective was to study between treatment effects and model their relationships mathematically. If the treatments were performed for very long durations, for example one day, it would have been prohibitively difficulty to test all treatments on all participants in a within-subjects experimental design, as was performed.

It was not the intention of the study to define actual limits for industrial work, but to study the profile of the relationship between DCT and the risk factors of force and exertion period for a short cycle task. The addition of the DCT action limit to the profile (Figure 5) appears an attractive approach for defining a more detailed and more comprehensive combined DCT evaluation approach. This requires testing of more risk factors and for longer durations of time for the data to be used in setting times in industry.

The study used DCT as the inference for productivity but this does not fit the pure definition, which is inputs/outputs. It also assumes that all exertion time is value-added and that there is no waste component, which some may say is almost impossible to achieve. It does however indicate that for high DCT conditions there should be greater availability of labour. Actually, the model suggests that longer duration exertions rather than shorter more frequent cycles will achieve higher output. Output viewed purely as increased frequency of cycles may not necessarily be an accurate measure of productivity. Furthermore, increased frequency of cycles will increase the level of repetition in a task and this has been proven to be related to risk of injury (Silverstein et al. 1986). The outcome is that longer cycle tasks involving greater numbers and variety of subtasks may be more beneficial for health and productivity combined than very short cycle high repetitive tasks.

This study only tested the neutral wrist posture with the forearm prone. Abu- Ali et al. (1996) found a significant three-way interaction between the effects of posture, force and duration of exertion on rest time. Moore and Wells (2005) also noted that deviated postures may effect psychophysically determined rest times and therefore cycle times. It is intended to address posture effects in future experimentation.

5. Conclusions

This study found a significant effect of force, exertion period and their interaction on Duty Cycle time, the productivity measure. Productivity decreased with increasing force and reduction in exertion duration. There were also significant effects of force and exertion period on discomfort, which was also significantly correlated with the productivity measure ($r<0.05$). A discomfort action limit was applied to the DCT data and this identified combinations of force and exertion that are considered acceptable. A highly significant and accurate regression model was fitted to the DCT data based on force, exertion duration and their interaction ($R^2 = 0.98$, $p<0.001$). Profiles were generated which predict the effects of changes to the predictor variables on DCT. Acceptable and unacceptable combinations of force and exertion duration, determined from the discomfort data analysis, are delineated on the DCT profile.

6 Acknowledgements

This work was completed on the Cybermans project, funded under the 6th Framework Programme (IST-NMP 016712)

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Equation 2 DCT multiple linear regression model

$$\mathrm{DCT} = ((\mathrm{sine}(48.25 - 1.62\,(\ln\mathrm{Force} * \mathrm{Exertion}) + 12.89\mathrm{Exertion} - 4.52\ln\mathrm{Force})/100))^{2}) * 100$$

Force = % MVC
Exertion = time in seconds
Sine = Radians

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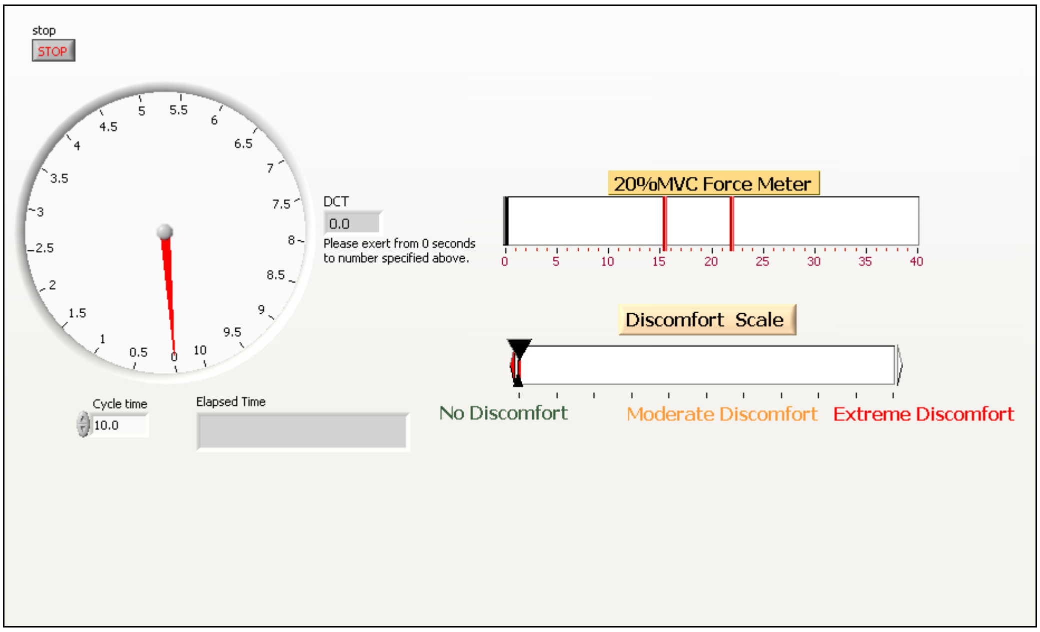
Figure 11 Experiment Rig



DCT 0.0

Please exert from 0 seconds to number specified above.

Cycle time 10.0

Figure 12 Screen shot of Labview interface

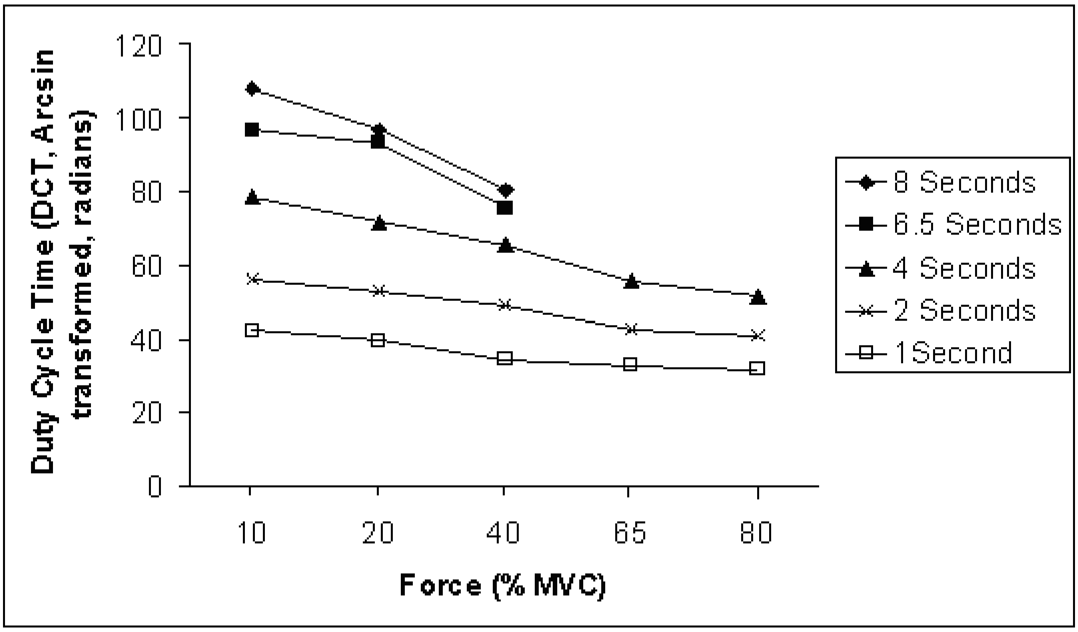


Figure 13 Duty Cycle Time (transformed) for Force versus Exertion duration

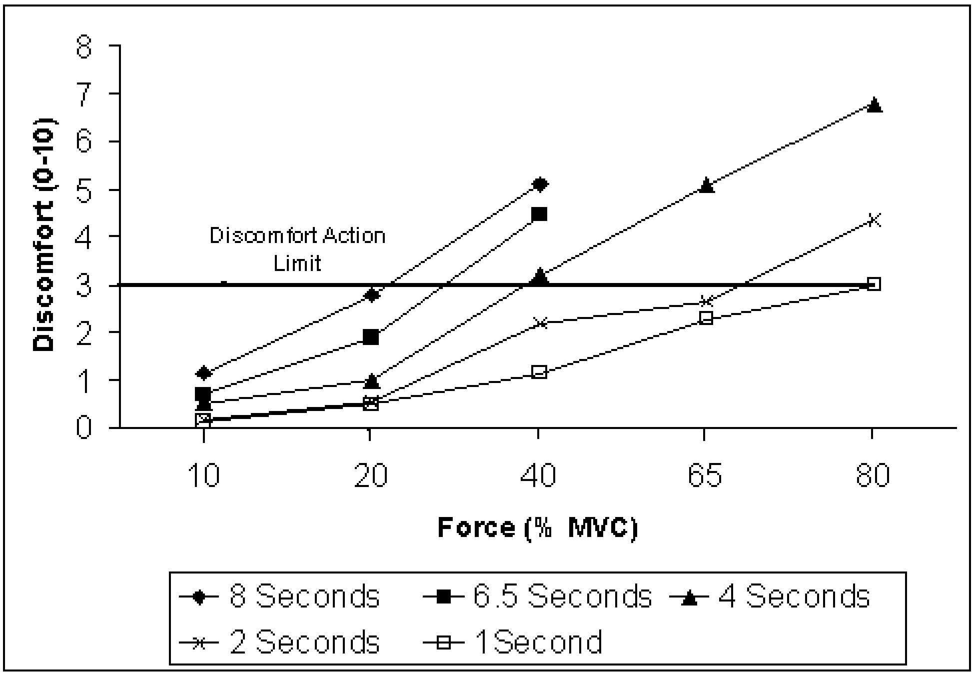


Figure 14 Raw Discomfort for Force versus exertion period

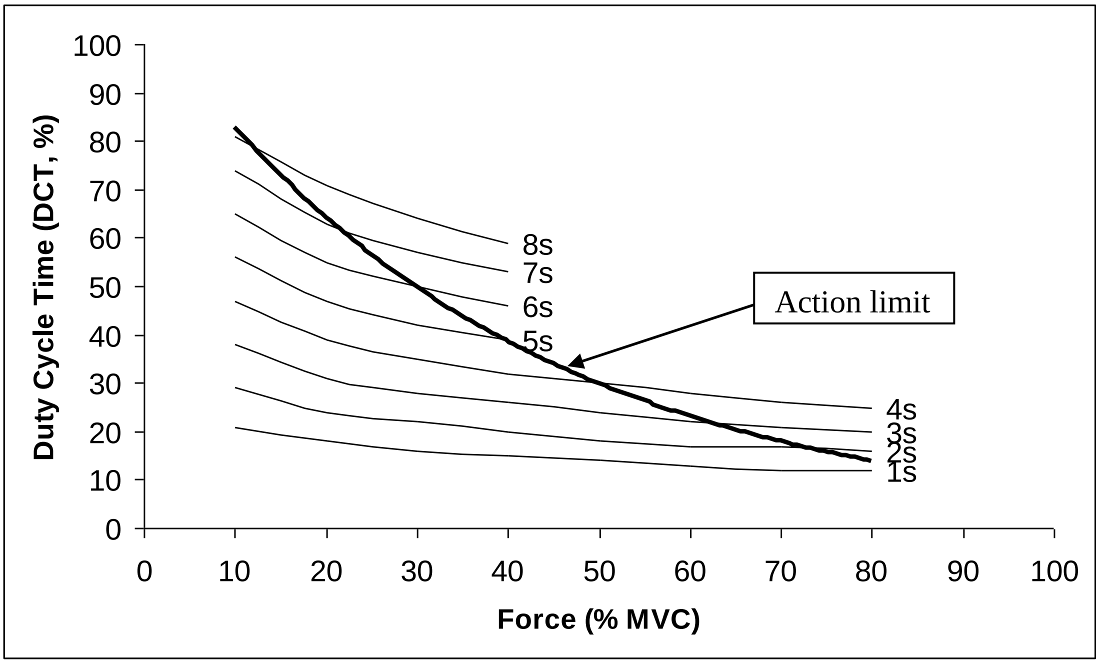


Figure 15 Profile generated from the DCT regression model with action limit

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Table 9 Analysis of Variance on DCT at 10 minutes

Factor	DF	MS	F	Sig.
Force	4	5862.5	67.6	0.0001
Exertion	4	37407	444.4	0.0001
Participant	20	467.7	4.175	0.0001
Force * Exertion	12	463.6	9.49	0.0001
Participant*Force	80	86.5	1.77	0.0001
Participant*Exertion	80	84.17	1.72	0.001
Error	420	83		

Table 10 Post hoc analysis of DCT data

Factor		Subset 1	Subset 2	Subset 3	Subset 4	Subset 5
Force	10% MVC	76.3				
	20% MVC		70.8			
	40% MVC			61.0		
	65% MVC				43.7	
	80% MVC				41.4	
Exertion	1 Seconds	36.1				
	2 Seconds		48.3			
	4 Seconds			64.6		
	6.5 Seconds				88.6	
	8 Seconds					94.9

Table 11 Mean and Standard Deviation (SD) DCT values by force and exertion

	Factors	DCT % (raw)		DCT % (transformed)	
Exertion duration (seconds)	Force (%MVC)	Mean	SD	Mean	SD
1	10	17.07	5.07	42.25	6.5
	20	15.05	3.69	39.61	5.03
	40	13.29	3.15	37.01	4.61
	65	10.56	2.57	32.92	3.91
	80	9.68	1.18	31.58	2.03
2	10	28.47	7.86	55.99	8.53
	20	25.84	6.11	53.1	6.79
	40	22.62	6.94	49.17	8.14
	65	17.11	3.27	42.49	4.31
	80	16.07	3.23	41.07	4.45
4	10	50.02	11.35	78.75	11.94
	20	43.11	5.49	71.59	5.57
	40	37.39	8.1	65.58	8.69
	65	28.43	9.2	55.84	10.11
	80	24.73	7.45	51.65	8.57
6.5	10	67.61	9.77	96.93	10.57
	20	63.97	13	93.29	14.38
	40	49.77	14.22	78.38	14.74
8	10	77.25	8.32	107.84	9.38
	20	67.03	13.67	96.59	14.61
	40	51.75	14.82	80.57	15.54

Table 12 Comparison of DCT values study

		DCT predictions (%)	
Exertion duration	% MVC	Abu-Ali et al.	Present study
1	25	36.6	16.2
1	50	18.3	13.2
5	25	56.3	43.6
5	50	38.1	35.0