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Effect of Ergonomic Design Changes in Hand Tools on Physiological Cost and Subjective Ratings

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Users of hand tools expect that tools after ergonomic changes in design will require less muscular activity and cause fewer musculoskeletal disorders than conventional tools. Reports on evaluation of ergonomic design changes in hand tools are controversial. In this study, we measured the effect of changes in tool design with physiological cost of performance and subjective ratings in a simulated setting. We determined physiological cost of performance by measuring muscle activity of the right and left forearm (flexor carpi ulnaris) with electromyography. We collected a questionnaire with subjective ratings before and after each experimental task. Before the tests, ergonomically reconfigured hacksaws received better rating scores than original hacksaws. However, we found no differences in subjective ratings of the hacksaws after the tests. In addition, electromyographic activity did not show any significant differences between the original and modified tools.

ergonomic design   hand tools   electromyographic activity   subjective assessments
Cronbach's α

1. Introduction

Hand tools are frequently used in industry and at home despite the development of mechanization and automation. Using hand tools can cause musculoskeletal disorders in the long term [1, 2]. Risk factors causing these disorders include awkward hand postures, excessive muscular load and fatigue, some types of required grips, and repeated use. The relation between tool design and development of musculoskeletal disorders in the hand and forearm has been shown for many tools, e.g., wire-tying pliers [3, 4, 5], hammers [4], powered screwdrivers [6], and plate shears [7]. Improvements in ergonomics characteristics of hand tools may be essential to reduce the risk of musculoskeletal disorders, as ergonomically designed hand tools cause users less harm, require less effort, and provide more comfort at work. Several studies have suggested ergonomics criteria for hand tool design relevant in terms of biomechanical and physiological stress [8, 9, 10, 11, 12]. Even though it is expected that taking into account ergonomics criteria of design will result in a better hand tool, labelled as an ergonomically designed one, an evaluation is necessary.

Designing hand tools is a complex task as it requires considering not only functionality, quality, and reliability, but also their users expectations and apprehensions. To integrate those requirements into tool design processes, several studies used the concept of quality function deployment, which allows designers to implement ergonomics at the very beginning of product development [7, 13, 14]. The ergonomic quality of hand tools can be evaluated by their performance and users physiological strain with different design variables such as shape, thickness, length, volume, surface quality, and material of tool handles. Electromyography (EMG), grip force and distribution, and hand and wrist postures are used to evaluate performance and physiological strain objectively,

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and questionnaires or ratings with various scales are used for subjective assessment. In the literature, a number of studies compared physiological cost of localized muscle strain and subjective assessment to evaluate ergonomic quality of hand tools, e.g., masons trowels [15], pruning shears [13], orbital sanders [16], wire-tying pliers [17], and screwdrivers [18]. Interestingly, the effect of ergonomic changes varied from one tool to another. The relation between physiological cost and subjective assessment was inconsistent. Li found that using ergonomically designed wire-tying pliers caused significantly lower physiological cost measured with EMG and better total satisfaction scores in subjective ratings than conventional pliers [17]. However, there was no significant difference in EMG measures among alternatively designed pliers even though subjective ratings differed. Meanwhile, Strasser, Wang, and Hoffmann found that EMG measures on target muscles were similar among the users of a mason s trowel with an ergonomically modified handle and of two standard models [15]. Interestingly, Spielholz, Bao, and Howard reported very little difference in physical measurements of hand force and movements while measuring arm and wrist postures, motions, and muscle activity during the use of standard orbital sanders and an ergonomically designed sander [16]. Controversially, the users strongly preferred the standard tool configuration to the new version.

Effect of ergonomic changes in hand tool designs on physiological cost and users preferences may be influenced by the acceptability of a new method, familiarity with a tool or process, and psychological reactions to the change. The objective of the study was to investigate effect of ergonomic changes in design of hand tools on physiological cost and subjective assessment. Non powered handsaws that usually bend the wrist of the left hand underwent some design changes.

2. METHODS

2.1. Participants

Twenty-two participants (9 males and 13 females), aged 15–17, were recruited from the summer program Innovative Technology Experiences for Students and Teachers at East Carolina University. All participants were free from any known musculoskeletal injuries and had no previous experience in working with hand hacksaws. The objective of recruiting minors with no experience was to avoid any possible bias of assessment due to familiarity with a tool or psychological preference. We collected informed consent forms from the participants and their parents or guardians before the experiment.

2.2. Apparatus

We considered four configurations of hand hacksaws (Figure 1). Models A-1 and B-1 were standard configurations currently available on the market. Models A-2 and B-2 were alternative configurations that were to minimize awkward hand or wrist postures and eliminate unnecessary flexion and extension of the wrist. The alternative configurations used two different handle grips. Model A-2 had a straight bar separating fingers on the left hand grip and model B-2 had a round bar getting all fingers together on the grip. It was possible to adjust the angles of the grip to put the wrist in a neutral position. Figure 2 shows comparisons of the hand or wrist postures between the standard and alternative configurations.

We developed a questionnaire for participants to assess subjectively their preferences. The items it contained concerned the comfort of grip, awkwardness of posture, task completeness, appearance, and recommendation. A Likert scale (1—*strongly disagree,* 5—*strongly agree*) was used in the answers. Figure 3 shows a sample questionnaire.

2.3. Procedures

We introduced each participant to their laboratory task, which was to saw a steel pipe, held by a vise attached to a table, with each hacksaw (Figure 4). The dimensions of the steel pipe were 2.7 cm (outside diameter), 2.1 cm (inside diameter), and 0.3 cm (wall thickness). The experiment consisted of two phases: pre-perceptual-based evaluation and post-physiological-based evalu-

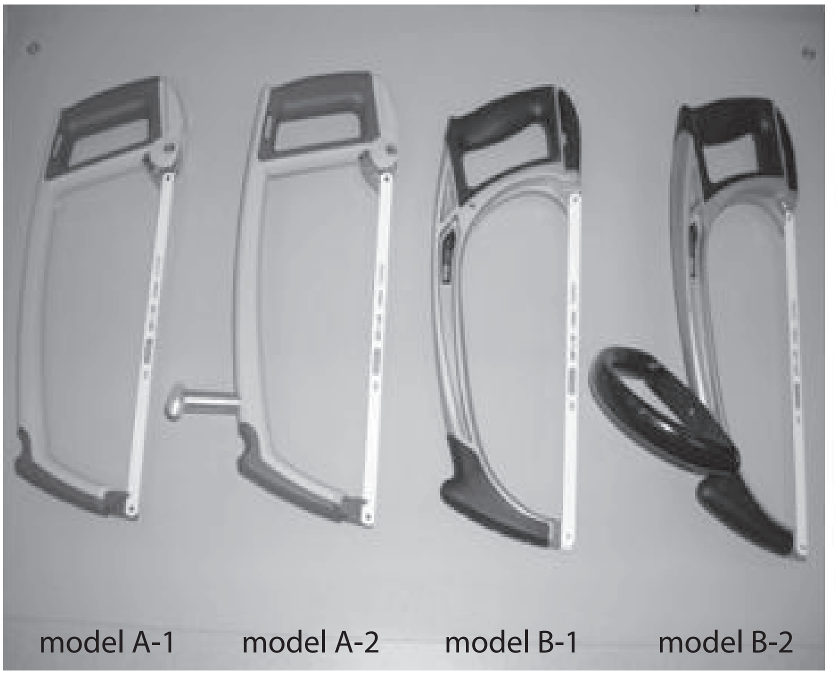

Figure 1. Four configurations of hacksaws.

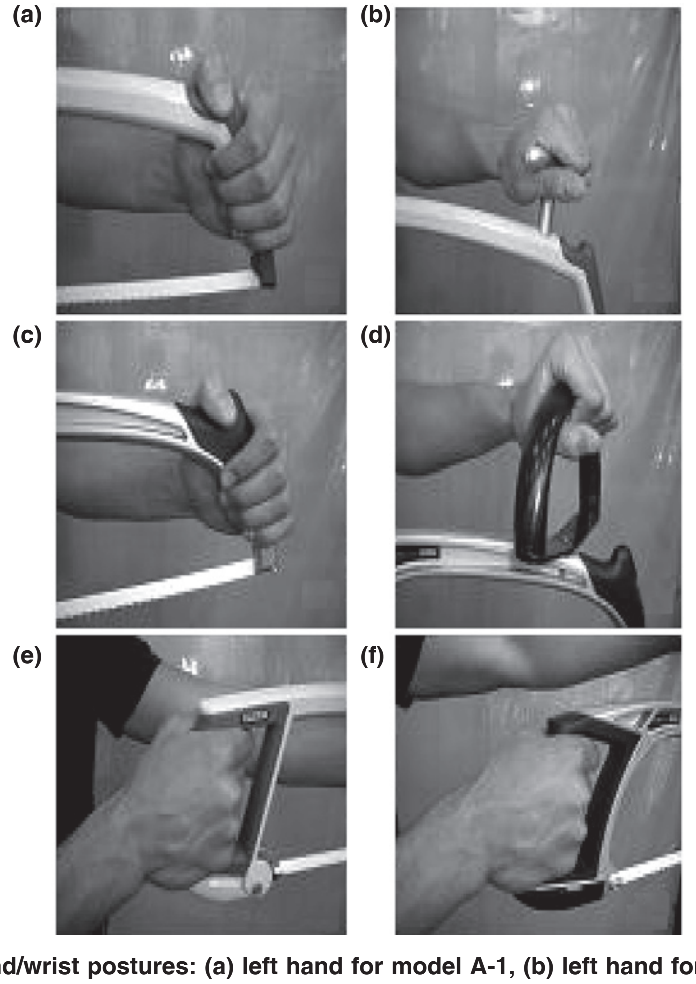

Figure 2. Hand/wrist postures: (a) left hand for model A-1, (b) left hand for model A-2, (c) left hand for model B-1, (d) left hand for model B-2, (e) right hand for model A-1 and A-2, and (f) right hand for model B-1 and B-2.

Tool Usability Questionnaire

Please complete the following questions on the basis of your feelings as best as you can. Circle your best answer for each question. You can just estimate the level as closely as possible if you are not quite sure your feelings.

1. Feel comfortable on the left hand grip.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

2. Feel that you can complete the cutting task satisfactorily.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

3. The design and appearance of the hacksaw looks great.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

4. If I need to buy one, I am willing to buy this hacksaw.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

5. I will recommend this hacksaw to other people.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

6. Overall I will rate this hacksaw very high.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
(1)	(2)	(3)	(4)	(5)

Figure 3. A sample subjective evaluation questionnaire for hacksaw design.

ation. In the pre-perceptual-based evaluation phase, the participants had a chance to examine each hacksaw by grasping it and mimicking sawing motion. Then they completed the questionnaire before the experimental pipe cutting task. In the post-physiological-based evaluation phase, a set of MyoScan-Pro (Thought Technology, Canada) EMG surface electrodes was placed over the flexor carpi ulnaris of the right and left forearms. The activity of the flexor carpi ulnaris was used to measure the wrist movements such as flexion, extension, radial deviation, and ulnar deviation [4, 6, 15, 17, 18, 19]. The preparation of the skin for the EMG surface electrodes was based on Toussaint, van Baar, van Langen, et al.'s procedure [20]. We amplified and filtered the EMG signals at the band pass of 20–400 Hz. The rectified and integrated root-mean-square (RMS) values were sampled into a computer at a rate of 2 000 samples per second. The sensitivity of RMS was under 0.3 μV. We used the BioGraph Infinite (Thought Technology, Canada) software to collect and process the EMG data. The normalization procedure [21] consisted in obtaining a 5-s measurement of a maximum voluntary contraction (MVC) power grip. MVC was measured with a hand dynamometer in three trials with a 1-min break between each trial [22]. All the EMG values were normalized as percentage of MVC (%MVC). Each participant used the hacksaws in a random order to saw a steel pipe. The task was performed for 2 min with a force comfortable for each participant. The degree of task performance such as the depth of cut of the pipe was not considered. The participants had a 3-min break between each task. After the tasks with all four hacksaws, the participants completed the same questionnaire for a post-evaluation.

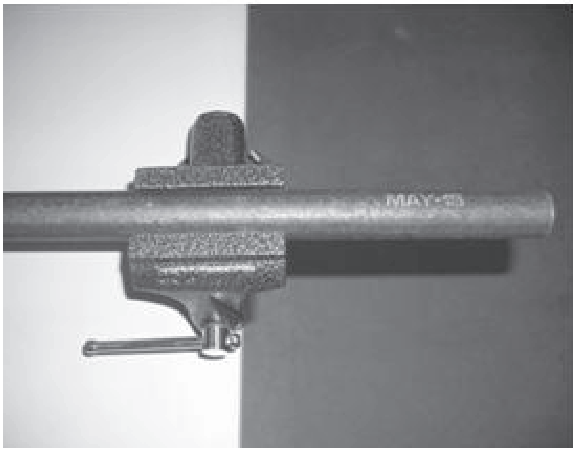

Figure 4. A steel pipe on a vise.

2.4. Data Analysis

The reliability of the subjective evaluation scale was assessed with Cronbach's α [23]. This is the most common approach to measuring internal consistency of items when scales are short, e.g., Likert scale. We determined the internal consistency with Cronbach's $\alpha > .7$ in a one-sided *F* test [23]. We examined differences in subjective ratings before and after the tests using a one-sided pair-wise *t* test for each tool after completing a normality test. An analysis of variance (ANOVA) for subjective scores and EMG (%MVC) tested the effect of the tools. We adopted a significance level of .05. In addition, Fisher's χ^2 test was used to compare the difference of rating scores for each questionnaire item before and after the tests.

3. RESULTS

Table 1 summarizes the anthropometric measurements. Each scale obtained Cronbach's α of .7 or better, suggesting that the subjective rating items were appropriate indicators of their respective constructs. Table 2 contains Cronbach's α for each tool before and after the tests.

TABLE 1. Anthropometric Characteristic of Participants

Parameter	*M*	*SD*
Age (years)	15.8	0.9
Right hand (cm)		
length	18.8	1.0
breadth	8.8	0.6
circumference	20.0	1.5
Left hand (cm)		
length	18.7	0.9
breadth	8.7	0.6
circumference	19.9	1.5

3.1. Subjective Evaluation of Tools Before and After Tests

Figures 5–6 present the results of a subjective assessment of the hand hacksaws before and after the tests, respectively. The bars in the figures represent mean values and standard deviation from the participants regarding the evaluation criteria. Before the tests, the two alternative configurations got higher scores than the standard configurations for all criteria except the aesthetic one. The results of ANOVA also showed a significant difference of scores for the configurations ($p \approx 0$) and criteria ($p < .0005$) (Table 3). However, after the tests, we found no significant

TABLE 2. Reliability Coefficients for Subjective Assessment Items

	Before Tests				After Tests			
Item	A-1	B-1	A-2	B-2	A-1	B-1	A-2	B-2
1	.87	.84	.90	.88	.90	.92	.89	.93
2	.88	.83	.88	.88	.91	.91	.89	.91
3	.90	.87	.90	.84	.96	.95	.92	.93
4	.86	.79	.89	.83	.90	.92	.87	.89
5	.87	.85	.92	.85	.91	.92	.90	.92
6	.84	.80	.88	.84	.90	.91	.88	.90

Notes. A-1, B-1, A-2, B-2—models of handsaws presented in Figure 1.

differences among all four configurations and six criteria from the results of ANOVA (Table 4). A pair-wise *t* test was performed to examine statistically the difference of scores after a normality test. Table 5 shows that the scores for items 1 ("feel comfortable on the left hand grip"), 2 ("feel that you can complete the cutting task satisfactorily"), and 6 ("overall I will rate this hacksaw very high") were significantly higher for the two standard configurations, model A-1 and B-1, after the tests. Meanwhile, no significant changes in scores were found for the two alternative configurations, model A-2 and B-2.

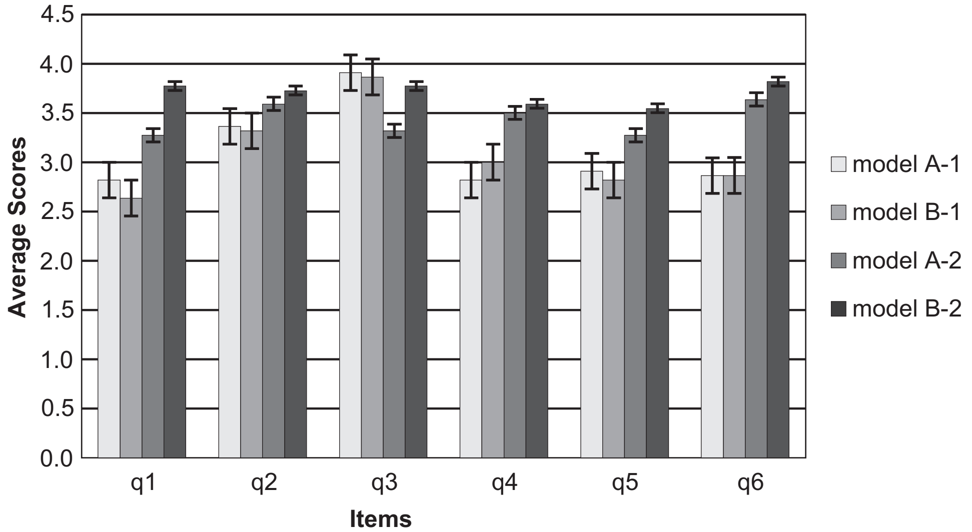

Figure 5. Subjective assessment scores before tests. *Notes*. q—questionnaire item. The bars in the figures represent mean values and standard deviation from the participants regarding the evaluation criteria.

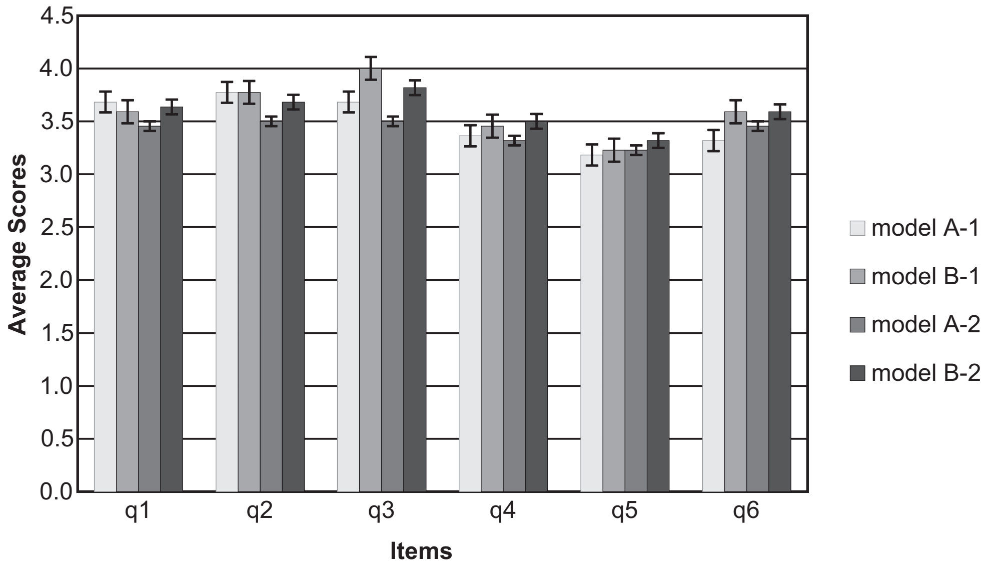

Figure 6. Subjective assessment scores after tests. *Notes*. q—questionnaire item, The bars in the figures represent mean values and standard deviation from the participants regarding the evaluation criteria.

TABLE 3. Analysis of Variance of Scores Before Tests

Source of Variation		*SS*	*df*	*MS*	*F*	*p*
Between hacksaws		34.09	3	11.36	11.11	≈0
Between questionnaire items		23.67	5	4.74	4.63	<.0005
Interaction		23.84	15	1.59	1.55	.0800
Within		515.73	504	1.02		
	total	597.33	527			

TABLE 4. Analysis of Variance of Scores After Tests

Source of Variation		*SS*	*df*	*MS*	*F*	*p*
Between hacksaws		3.29	3	1.09	0.89	.45
Between questionnaire items		15.52	5	3.10	2.49	.03
Interaction		3.18	15	0.21	0.17	.99
Within		625.64	504	1.24		
	total	647.63	527			

TABLE 5. Pair-Wise *t* Test of Subjective Scores Between Before and After the Tests

Survey Items	Model A-1	Model B-1	Model A-2	Model B-2
1	$t = –3.91$, $\mathbf{p < .01}$	$t = –4.48$, $\mathbf{p < .01}$	$t = –0.68$, $p > .05$	$t = 0.55$, $p > .05$
2	$t = –1.90$, $\mathbf{p < .05}$	$t = –1.94$, $\mathbf{p < .05}$	$t = 0.30$, $p > .05$	$t = 0.18$, $p > .05$
3	$t = 1.42$, $p > .05$	$t = –0.68$, $p > .05$	$t = –0.75$, $p > .05$	$t = –0.21$, $p > .05$
4	$t = –2.03$, $\mathbf{p < .05}$	$t = –1.69$, $p > .05$	$t = 0.58$, $p > .05$	$t = 0.34$, $p > .05$
5	$t = –1.00$, $p > .05$	$t = –2.00$, $\mathbf{p < .05}$	$t = 0.17$, $p > .05$	$t = 0.93$, $p > .05$
6	$t = –2.11$, $\mathbf{p < .05}$	$t = –2.84$, $\mathbf{p < .01}$	$t = 0.55$, $p > .05$	$t = 0.76$, $p > .05$

Notes. p values with significance at $\alpha = .05$ are in boldface.

TABLE 6. χ^2 Test Between Before and After the Tests for Each Model

Survey Items	Model A-1	Model B-1	Model A-2	Model B-2
q1	$p = .013$	invalid	$p = .014$	$p = .846$
q2	$p = .053$	invalid	$p = .101$	$p = .101$
q3	$p = .121$	invalid	$p = .271$	$p = .443$
q4	$p = .569$	invalid	$p = .675$	invalid
q5	$p = .706$	invalid	$p = .611$	$p = .580$
q6	$p = .606$	$p = .432$	$p = .187$	invalid

Notes. Invalid—χ^2 approximation is not valid because more than two cells of the χ^2 tabulation have expected counts <1.

In Fisher's χ^2 test subjective ratings were considered as nonparametric values. The ratings for models A-1 and B-1 showed significant changes before and after the tests for item 1 only. Table 6 shows a summary of the results.

3.2. EMG Activity for Both Arms

EMG in terms of %MVC was calculated with maximum and mean RMS during the tests for both forearms. Table 7 shows the ANOVA results for EMG (%MVC) of the flexor carpi ulnaris depending on the tools. The tool effects were insignificant for both forearms. A pair-wise comparison between the standard and alternative configuration, i.e., model A-1 versus A-2 and model B-1 versus B-2 was tested using a two-sided *t* test. All pairs showed insignificant differences in EMG. Figure 7 shows sample EMG RMS of the right and left arm of a participant during the tests using four tools. Time is on the horizontal axis and RMS on the vertical axis for each plot.

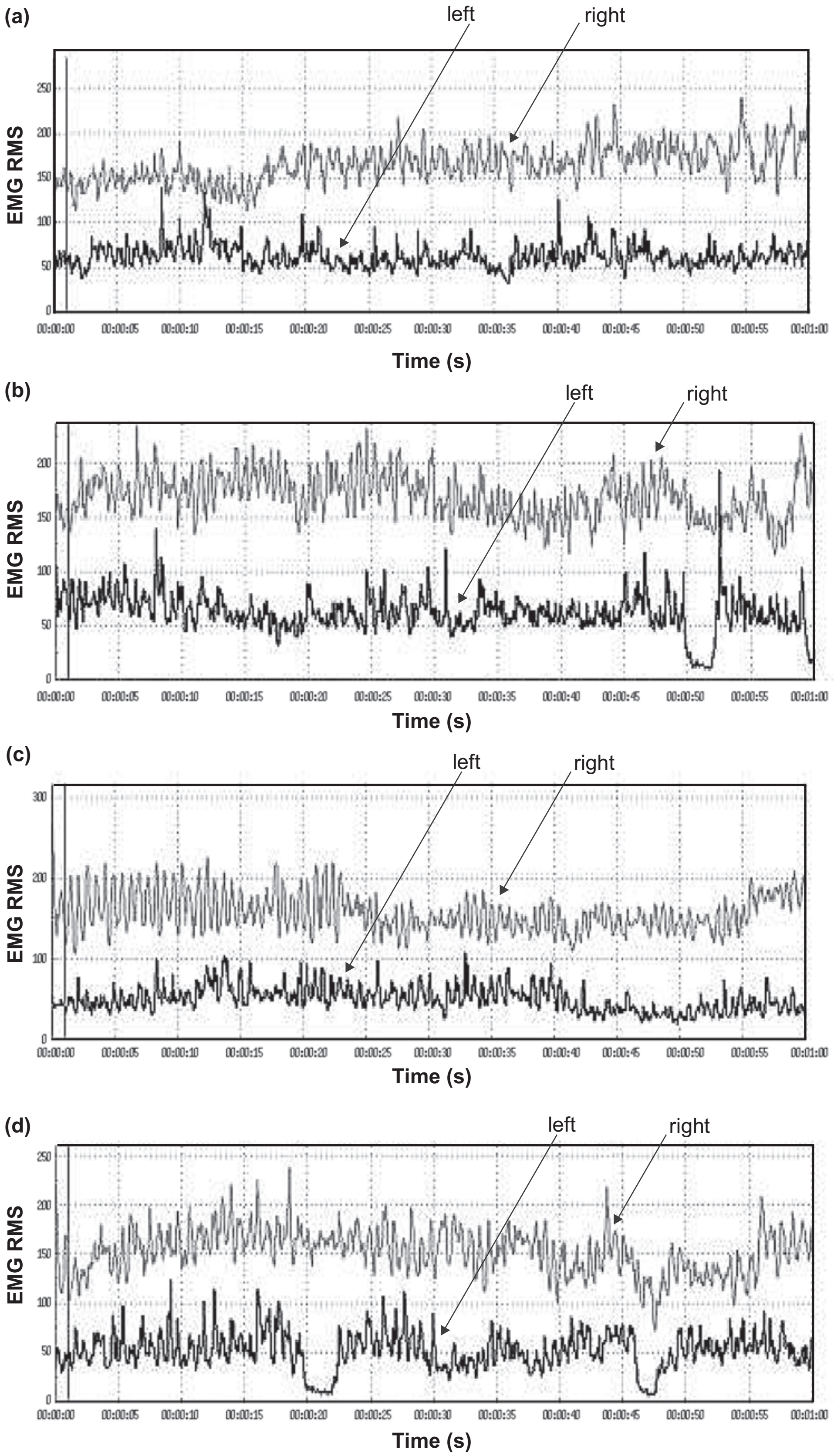

Figure 7. Sample electromyography root-mean-square (EMG RMS) of flexor carpi ulnaris of the right and left forearm using (a) model A-1, (b) model B-1, (c) model A-2, and (d) model B-2.

TABLE 7. Analysis of Variance of Electromyography (EMG)—Percentage of Maximum Voluntary Contraction (%MVC)

Arm	Source of Variation		*SS*	*df*	*MS*	*F*	*p*
Right	between-hacksaws		5518.13	3	1839.38	0.93	.43
	within-hacksaws		166952.30	84	1987.53		
		total	172470.40	87			
Left	between-hacksaws		139.77	3	46.59	0.05	.99
	within-hacksaws		81529.19	84	970.59		
		total	81668.96	87			

TABLE 8. Correlations Between Subjective Ratings and EMG (%MVC)

	Right Arm				Left Arm			
Item	A-1	B-1	A-2	B-2	A-1	B-1	A-2	B-2
1	−.04	.02	.19	.07	−.02	0	.11	−.37
2	−.18	−.14	.06	−.15	−.12	−.15	−.03	−.27
3	.29	.27	.47	.25	.22	.24	.39	.06
4	.05	.10	.15	.09	.07	.08	.04	−.13
5	.01	.06	.07	.11	.08	.08	.08	−.09
6	−.07	−.03	.21	.23	−.02	.02	.11	−.03

Notes. A-1, B-1, A-2, B-2—models of handsaws presented in Figure 1.

3.3. Correlation Between Subjective Rating and EMG Activity

We calculated the correlation coefficient between three subjective assessment items and EMG activity. The questionnaire items "feel comfortable on the left hand grip", "feel that you can complete the cutting task satisfactorily", and "overall I will rate this hacksaw very high" were selected because they showed a significant difference in subjective rating changes in the pair-wise *t* test. Table 8 summarizes the correlations between each subjective assessment item and EMG measurement for the right and left arm with four tools. We used the mean of EMG RMS values measured during the tests. Generally, correlations between subjective ratings and muscle activity were low [24].

4. DISCUSSION

Several studies reported incompatible outcomes between subjective ratings and EMG activity in evaluations of hand tools [15, 18, 19]. For instance, although some ergonomically configured hand tools scored significantly better in subjective ratings than conventional hand tools, no significant difference in muscle activity was found between modified and conventional designs. Contrary to previous results, this study showed that subjective ratings and EMG activity were compatible after actual interaction with tools. In the pre-perceptual-based evaluation phase before the tests, alternatively designed tools with ergonomic changes received higher subjective ratings in most assessment items. Participants could have expected ergonomically designed tools to be more comfortable and functional in completing the task. However, in the post-physiological-based evaluation phase after the test, subjective ratings were not significantly different between the tools for all the assessment items. Only the subjective rating for the item 1 was changed for the conventional designs of model A-1 and B-1 from parametric and nonparametric tests. However, an analysis of the results of the χ^2 test showed many invalid *p*s. Although this study had a relatively large sample size compared to previous studies [4, 6, 15, 17, 18, 19], more samples are necessary to validate the χ^2 test.

Maximum and mean RMS values (%MVC) for both arms were not significantly different among the tools. According to Spielholz et al. [16] and Strasser [19], ergonomically designed tools failed to show a significant reduction in physiological cost if their fundamental operating methods were the same as standard ones and postures or grips changed little. However, when alternatively designed tools required quite different manoeuvring, physical cost measured with EMG decreased significantly [17]. Following this study and previous reports, evaluation of ergonomic design should include hand–arm compatible interfaces for manual tool operating methods. The human–tool interface, such as hand–arm movement characteristics, should be assessed subjectively and objectively prior to capital investments.

Since familiarity with a tool, process, or work environment can affect users preferences, subjective ratings may not be free from bias and uncontrollable transferring effect. However, the result of this study with inexperienced users was similar to the result of a previous report with experienced users evaluating orbital sander configurations [16]. Thus, it can be assumed that the effect of experience with tools on subjective ratings is negligible.

There are many good examples of ergonomically designed hand tools that can improve the ease of use, comfort, or functionality, while reducing physiological cost. A trustworthy assessment of the ergonomic quality of a hand tool must rely on subjective ratings and work-physiological measurements with tests based on interactions with tools.

REFERENCES

1. Aghazadeh F, Mital A. Injuries due to hand tools. Results of a questionnaire. Appl Ergon. 1987;18(4):273–8.
2. Chao A, Kumar AJ, Emery CTND, Nagarajarao K, You H. An ergonomic evaluation of cleco pliers. In: Proceedings of the IEA 2000/HFES 2000 Congress, San Diego, California, USA. Santa Monica, CA, USA: Human Factors and Ergonomic Society; 2000. p. 4-441–2.
3. Emanual J, Mills S, Bennett J. In search of a better handle. In: Poydar HR, editor. Proceedings of the Symposium: Human Factors and Industrial Design in Consumer Products. Medford, MA, USA: Tuffs University; 1980. p. 34–40.
4. Schoenmarklin RW, Marras WS. Effects of handle angle and work orientation on hammering: I. Wrist motion and hammering performance. Hum Factors. 1989;31(4):397–411.
5. Tichauer ER. Some aspects of stress on forearm and hand in industry. J Occup Med. 1966;8(2):63–71.
6. Johnson S. Evaluation of powered screwdriver design characteristics. Hum Factors. 1988;30(1):61–9.
7. Kilbom Å, Makarainen M, Sperling L, Kadefors R, Liedberg L. The significance of tool design and individual factors for efficiency and fatigue in work with plate shears. Stockholm, Sweden: Swedish Institute of Occupational Health; 1991.
8. Chaffin DB, Anderson GBJ. Occupational biomechanics. New York, NY, USA: Wiley-Interscience; 1984.
9. Greenberg L, Chaffin DB. Workers and their tools: a guide to the ergonomic design of handtools and small presses. Midland, MI, USA: Pendell; 1978.
10. Meagher SW. Tool design for prevention of hand and wrist injuries. J Hand Surg Am. 1987;12(5 Pt 2):855–7.
11. Putz-Anderson V, editor. Cumulative trauma disorders. A manual for musculoskeletal diseases of the upper limb. London, UK: Taylor & Francis; 1988.
12. Schoenmarklin RW, Marras WS, Leurgans SE. Industrial wrist motions and incidence of hand/wrist cumulative trauma disorders. Ergonomics. 1994;37(9): 1449–59.
13. Haapalainen MJ, Kivistö-Rahnasto J, Mattila M. Ergonomic design of non-powered hand tools: an application of quality function deployment. Occup Ergon. 1999/2000;2(3):179–89.
14. Marsot J, Claudon L. Design and ergonomics. Methods for integrating ergonomics at hand tool design stage. International Journal of Occupational Safety and Ergonomics (JOSE). 2004;10(1):13–23. Retrieved May 8, 2012, from: http://www.ciop.pl/8662

15. Strasser H, Wang B, Hoffmann A. Electromyographic and subjective evaluation of hand tools: the example of masons trowels. Int J Ind Ergon. 1996;18(1):91–106.
16. Spielholz P, Bao S, Howard N. A practical method for ergonomic and usability evaluation of hand tools: a comparison of three random orbital sander configurations. Appl Occup Environ Hyg. 2001;16(11):1043–8.
17. Li KW. Ergonomic design and evaluation of wire-tying hand tools. Int J Ind Ergon. 2002;30(3):149–61.
18. Ozalp T, Babalik FC. Ergonomic evaluation of screwdriver handles under different working conditions. Occup Ergon. 2005;5:187–203.
19. Strasser H. Different grips of screwdrivers evaluated by means of measuring maximum torque, subjective rating and by registering electromyographic data during static and dynamic test work. In: Karwowski W, Yates JW, editors. Advances in industrial ergonomics and safety III. New York, NY, USA: Taylor & Francis; 1991. p. 413–20.
20. Toussaint HM, van Baar CE, van Langen PP, de Looze MP, van Dieën JH. Coordination of the leg muscles in backlift and leglift. J Biomech. 1992;25:1279–89.
21. Mirka GA, Marras WS. Toward a more accurate description of the EMG/force relationship of the erector spinae muscles. In: Proceedings of the Human Factors Society 35th Annual Meeting. Santa Monica, CA, USA: Human Factors Society; 1991. p. 728–32.
22. Rohmert W. Problems of determination of rest allowances Part 2: determining rest allowances in different human tasks. Appl Ergon. 1973;4(3):158–62.
23. Cronbach LJ. Coefficient alpha and the internal structure of tests. Psychometrika. 1951;16(3):297–334.
24. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Mahwah, NJ, USA: Erlbaum; 1988.