Ergonomic Evaluation on Handle Designs of Vacuum Cleaner

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Previous studies of handle evaluation have mainly examined optimal sizes of simple-shape (e.g., cylindrical) handles. The present study was intended to identify main design factors and to evaluate usability of vacuum cleaner handles which have complex design features. Upper part length (UL), midpoint-pipe centerline distance (MCD), tilt angle (TA), and cross-section upper part curvature radius (UR) of handle were determined as main design factors of vacuum cleaner handle. The effects of the four design factors on motion, muscular effort, and satisfaction in a front-to-back vacuuming task were evaluated using 6 handles by 36 participants aged in 20s to 50s. The ergonomic evaluation showed that the comfortable range of motion (CROM) deviations of small TAs (40.6° ~ 46.6°) were 1.8% higher significantly in abduction/adduction of shoulder, 2.6% lower in flexion/extension of shoulder, 1.6% lower in ulnar/radial deviation of wrist compared to those of large TAs (56.6° ~ 64.7°). Furthermore, % MVC < 5% of small URs (4.9 ~ 13.3 mm) was 1.7% higher significantly in deltoid, 3.0% higher in flexor carpi radialis compared to those of large URs (17.8 ~ 19.9 mm). Significantly higher satisfaction levels were reported in long ULs (118.4 ~ 154.8 mm) than short ULs (68.7 ~ 98.2 mm) and in short MCDs (3.0 ~ 25.8 mm) than long MCDs (39.4 ~ 78.4 mm). The results of this study can be used to develop ergonomic handles of vacuum cleaner.

INTRODUCTION

Handles of vacuum cleaner need to be ergonomically designed for better usability. A prolonged use of a vacuum cleaner with an improperly designed handle can result in discomfort at the shoulder, forearm, and wrist (Hu et al., 2013). Studies regarding hand tool design indicated that handle design can significantly affect motion and muscular effort of shoulder, forearm, and wrist (Aghazadeh and Mital, 1987; Eksioglu, 2004; Meagher, 1987; Schoenmarkhlin and Marras, 1989a, 1989b; Tichauer and Gage, 1977). Using an improperly designed handle for a long time can cause cumulative trauma disorders of the user's hand and forearm (Eksioglu, 2004). An ergonomically designed handle can contribute to improving convenience, muscular efficiency, performance, and satisfaction (Eksioglu, 2004; Harih and Dolsak, 2014; Bohlemann et al., 1994).

Previous studies regarding handle evaluation have investigated optimal sizes of simple-shape handles (e.g., cylindrical handle), but not expanded into complex-shape handles (e.g., vacuum cleaner handle). Existing studies have mainly evaluated diameters of cylindrical handles in terms of force exertion, EMG activity, and subjective satisfaction (Ayoub and Lo Presti, 1971; Bechtol, 1954; Blackwell et al., 1999; Drury, 1980; Johnson, 1988; Khalil, 1973; Montoye and Faulkner, 1965; Petrofsky et al., 1980). For example, Ayoub and Lo Presti (1971) found that among four handle diameters (3.2, 3.8, 5.1, 6.4 cm) the 3.8 cm handle diameter was the most efficient which produced the lowest grip force-to-EMG activity ratio. Drury (1980) identified that 3.1 to 3.8 cm handle diameters were subjectively preferred. However, the shapes of handle used in reality are usually complicated and the most desirable handle shape would depend on task (Cochran et al., 1986). Therefore, an evaluation on design factors of vacuum cleaner handle is needed to optimize the handle design for a vacuum cleaning task.

A handle design of vacuum cleaner considering motion, muscular effort, and satisfaction can improve performance and satisfaction. Lee et al. (2008) reported that products, which consider both motion and muscular effort, enable natural body movement, proper muscular effort, ease of operation, convenience, and satisfaction, and consequently result in improving work efficiency. Kinchington et al. (2012) and Kuijt-Evers et al. (2007) found that handle designs considering user satisfaction can enhance performance as well.

The present study was intended to identify main design factors of vacuum cleaner handle and evaluated vacuum cleaner handles with various design features in terms of motion, muscular effort, and satisfaction for better usability. Main design factors were determined with respect of length, distance, angle, and curvature by analyzing shapes of existing vacuum cleaner handles. The effects of main design factors on motion, muscular effort, and satisfaction in a front-to-back vacuum cleaning task were evaluated. Finally, the preferred properties of design factors that contribute to vacuum cleaner usability were identified from the ergonomic evaluation.

METHODS

Participants

In the ergonomic evaluation experiment, motion, muscular effort, and satisfaction were evaluated with participants using vacuum cleaners. To consider the effect of hand size on using vacuum cleaner handles, 36 participants (M: 18, F: 18; age = 35.5 ± 11.8 year; hand breadth = 81.2 ± 5.2 mm) were recruited evenly for three hand-size categories (small: ≤ 33rd percentile; medium: 33rd ~ 67th percentile; and large: ≥ 67th percentile using hand breadth data of Size Korea reported by Korea Agency for Technology and Standards in 2010) of Korean male and female each aged in 20s to 50s. The participants provided informed consent after a brief description of the experiment procedure was introduced.

Vacuum Cleaner Handles

Main design factors of vacuum cleaner handle affecting usability were analyzed and measured through a four-step procedure: (1) CAD data construction, (2) design factor analysis, (3) main design factor determination, and (4) design dimension measurement. First, the CAD data of 6 vacuum cleaner handles (coded as SSLS, LSSL, SLSS, SLLS, LSSL, and LSLS) with various shapes and sizes was constructed using digital handle scans acquired using a 3D hand scanner (Arctec 3D Eva, Artec Group, USA). Second, 26 design factors for various handle parts were defined in respect of length, distance, angle, and curvature. Third, of the design factors, upper part length (UL), midpoint-pipe centerline distance (MCD), tilt angle (TA), and cross-section upper part curvature radius (UR) of handle were determined as main design factors based on an importance evaluation result of design factors and opinions of a group of vacuum handle design practitioners and ergonomists. The importance evaluation of design factors was conducted to assess hand contact frequency and their effects on grip posture and hand contact area. Finally, the main design factors of 6 handles were measured using Alias Automotive 2012 (Autodesk Inc., USA), and divided into two groups by a referent of each main design factor as shown in Table 1.

Experiment Protocol

To measure the motion, EMG in vacuuming motion with the six different handles, a participant was instructed to conduct a front-to-back vacuuming motion while standing at a designated place. The motion was repeated 7 times with a pace of 60 bpm along an 850 mm line drawn on the floor to control motions between participants. The handles were used with the same nozzle and pipe of which length was adjusted by the participant for his/her best comfort for the task. The participant was asked to practice for about five minutes to be accustomed with the task and use of the handles prior to the main experiment. To exclude order effects, the order of handle was balanced with the Latin square design. The angles of shoulder adduction/abduction and flexion/extension and wrist ulnar/radial deviation and flexion/extension were measured using 6 infrared cameras (Motion Analysis Corp., Santa Rosa, CA, USA) at 50 Hz when performing the cleaning task. The joint center and body segment coordinate system in motion analysis were defined using 11 reflective markers (7th cervical bone, 6th thoracic bone, acromion, scapula, upper arm, elbow, forearm, ulna, radius, 2nd metacarpal bone, and 5th metacarpal bone; see Figure 1). To remove noise the motion data was filtered using fourth-order butterworth filter (cut-off frequency: 5 Hz).

Table 1. The level of main design factors of six vacuum cleaner handles

Design Factor	Image	Referent	SSLS	LSSL	SLSS	SLLS	LSSL	LSLS
Upper part length (UL)		120 mm	Short	Long	Short	Short	Long	Long
Midpoint-pipe centerline distance (MCD)		270 mm	Short	Short	Long	Long	Short	Short
Tilt angle (TA)		50°	Large	Small	Small	Large	Small	Large
Cross-section upper part curvature radius (UR)		15 mm	Small	Large	Small	Small	Large	Small

Note: the columns SSLS–LSLS are grouped under "Vacuum handles".

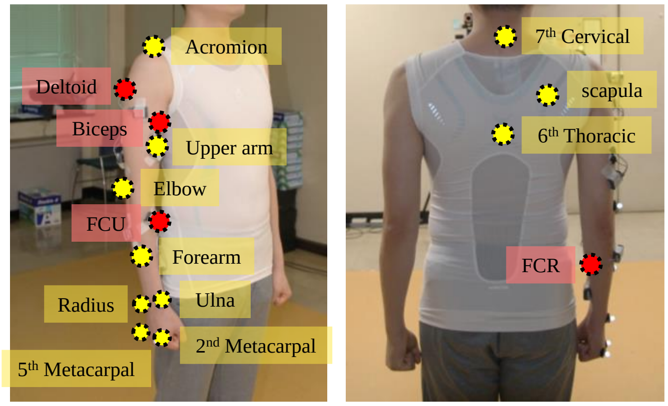


Figure 1. Attachment of 11 reflective markers and 4 EMG electrodes

EMG signals of four muscles (deltoid, biceps, flexor carpi ulnaris (FCU), and flexor carpi radialis (FCR); Figure 1) were measured in a vacuum cleaning task using Telemyo DTS Telemetry (Noraxon, USA). Maximum voluntary contractions (MVCs) prior to the experiment and EMG signals during the cleaning task were measured by attaching electrodes and using the wireless EMG signal transmitter/receiver at 1,000 Hz. Noises of EMG signals were filtered by applying bandpass filter (cut-off frequency: lower - 10 Hz and upper - 400 Hz) and then smoothed by applying root mean square (time window: 400 ms) for analysis of amplitude.

Satisfaction of the five vacuum handles (LSSL, SLSS, SLLS, LSSL, LSLS) was relatively evaluated compared to a reference handle (SSLS) using 5-point bipolar scale (-5: strongly dissatisfied; 0: neutral; 5: strongly satisfied). Detailed satisfaction measures such as appropriateness of UL, appropriateness of MCD, appropriateness of TA, appropriateness of UR, and overall satisfaction were assessed considering their relationships with the major design factors of vacuum cleaner handle. Motion, muscular effort, and satisfaction were analyzed using comfortable range of motion (CROM) deviation, %MVC, and satisfaction score, respectively. CROM deviation was calculated as the number of motion frames beyond CROM (shoulder adduction/ abduction: -5° ~ -65°; shoulder flexion/extension: 31° ~ -10°; wrist ulnar/radial deviation: 5° ~ -10°; and wrist flexion/ extension: 15° ~ -15°; Figure 2) proposed by Chaffin et al. (2006) divided by the total number of motion frames. Muscular effort was evaluated as the number of EMG values

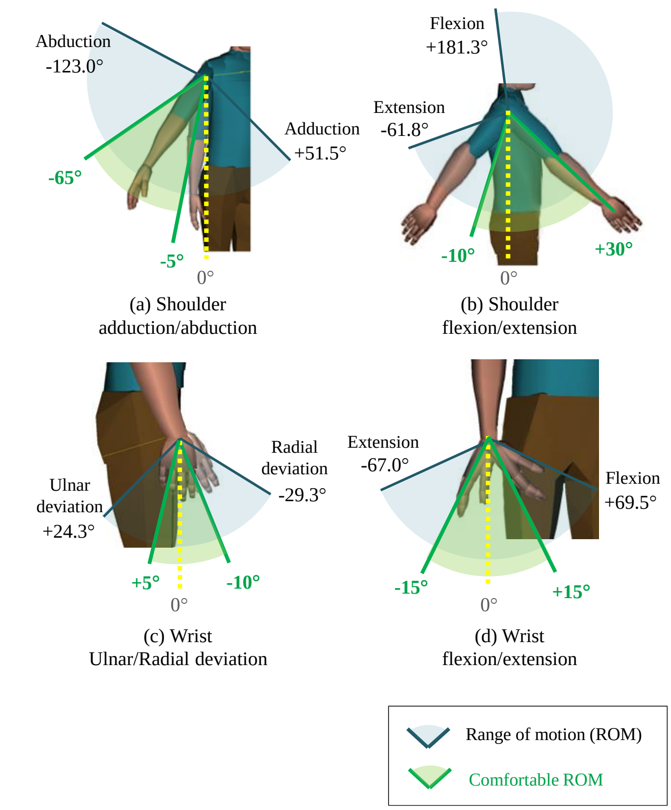


Figure 2. Ranges of motion (ROMs; colored blue) and comfortable ROMs (CROM; colored green) of shoulder and wrist (Chaffin et al., 2006)

lower than 5% MVC divided by the total number of EMG values. The motion and EMG measurements of the first and last cleaning motions out of the seven repeated cleaning motions were excluded from the analysis. ANOVAs were conducted at α = 0.05 to examine the effects of four design factors (UR, MCD, TA, and UR) with two treatments on motion, muscular effort, and satisfaction.

RESULTS

Motion

The mean CROM deviations between tilt angles (TAs) of vacuum handle showed significant differences in abduction/ adduction and flexion/extension of shoulder and ulnar/radial deviation and flexion/extension of wrist. As shown in Figure 3, in abduction/adduction of shoulder the CROM deviation ($M \pm SD$ = 12.8% ± 19.0%) of the small TA (40.6° ~ 46.6°) was 1.8% higher (F[1, 600] = 5.58, p = 0.02) compared to that (11.0% ± 19.2%) of the large TA (56.6° ~ 64.7°); in flexion/extension of shoulder, the CROM deviation (46.3% ± 8.3%) of the small TA 2.6% lower (F[1, 602] = 15.31, p < 0.001) compared to that (48.7% ± 7.6%) of the large TA; in ulnar/radial deviation of wrist, the CROM deviation (60.6% ± 24.1%) of the small TA 1.6% lower (F[1, 615] = 15.60, p < 0.001) compared to that (62.2% ± 23.7%) of the large TA. In flexion/extension of wrist, the CROM deviation (38.7% ± 36.6%) of the small TA 4.3% lower compared to that (43.0% ± 37.9%) of the large TA.

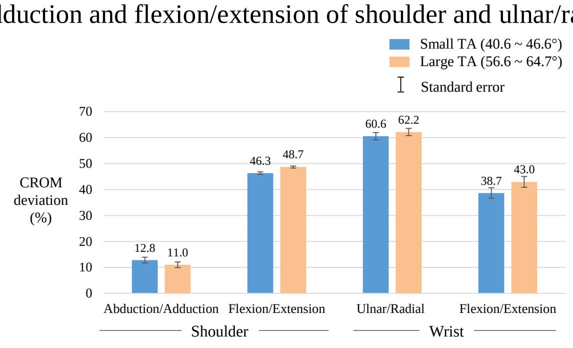


Figure 3. Comparison of the small tilt angle (TA) and large TA groups in CROM deviation

Electromyography

The muscular efforts between cross-section upper part curvature radiuses (URs) of vacuum handle showed significant differences in deltoid and FCR, but not in biceps and FCR. As shown in Figure 4, in deltoid, % MVC < 5% (M ± SD = 23.7 ± 21.1%) of the small UR (4.9 ~ 13.3 mm) was 1.7% higher (F[1, 613] = 5.73, p = 0.02) compared to that (22.0 ± 19.3%) of the large UR (17.8 ~ 19.9 mm); in FCR, % MVC < 5% (21.5 ± 24.0%) of the small UR 3.0% higher (F[1, 591] = 9.02, p < 0.001) compared to that (18.5 ± 22.2%) of the large UR. In biceps, % MVC < 5% (50.9 ± 34.0%) of the small UR was 2.3% lower compared to that (53.2 ± 35.2%) of the large UR; in FCU, % MVC < 5% (18.6 ± 22.6%) of the small UR 7.5% lower compared to that (26.1 ± 31.8%) of the large UR.

Satisfaction

Higher satisfaction levels were found in the longer upper part length (UL), shorter midpoint-pipe centerline distance (MCD), larger tilt angle (TA), and larger cross-section upper part curvature radius (UR) of vacuum handle. The UL appropriateness (M ± SD = 1.0 ± 1.9) of the long UL (118.4 mm ~ 154.8 mm) was 1.0 higher (F[1, 211] = 5.37, p = 0.02) compared to that (0.0 ± 1.7) of the short UL (68.7 mm ~ 98.2 mm). The MCD appropriateness (0.8 ± 1.4) of the short MCD (3.0 mm ~ 25.8 mm) was 0.4 higher (F[1, 211] = 4.98, p = 0.03) compared to that (0.4 ± 1.8) of the long MCD (39.4 mm ~ 78.4 mm). The TA appropriateness (0.6 ± 1.8) of the large

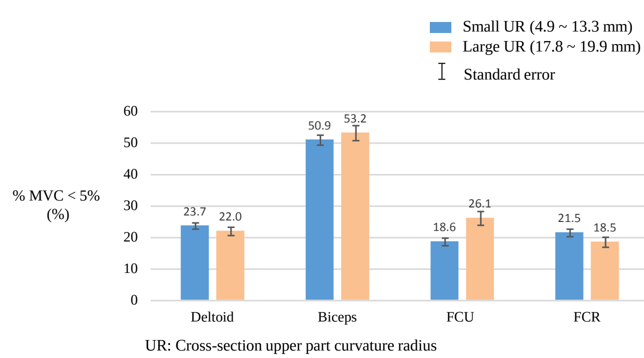
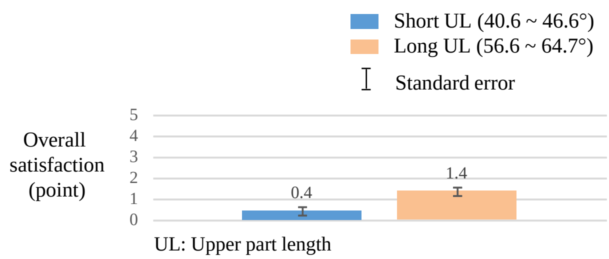
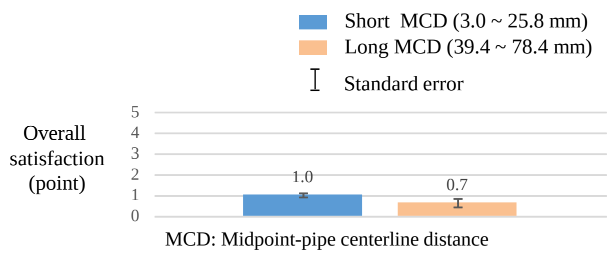


Figure 4. Comparison of the small cross-section upper part curvature radius (UR) and large UR groups in % MVC < 5%



(a) Comparison of short upper part length (UL) group and long UL group in overall satisfaction



(b) Comparison of short midpoint-pipe centerline distance group (MCD) and long MCD group in overall satisfaction

Figure 5. Comparison of satisfaction evaluation for upper part length and midpoint-pipe centerline distance

TA (56.6° ~ 64.7°) was 0.1 higher compared to that (0.5 ± 1.6) of the small TA (40.6° ~ 46.6°). The UR appropriateness (0.7 ± 1.7) of the large UR (17.8 ~ 19.9 mm) was 0.7 higher compared to that (0.0 ± 1.8) of the small UR (4.9 ~ 13.3 mm).

Overall satisfaction levels were found significantly higher in the long UL and short MCD of vacuum handle. As shown in Figure 5, The overall satisfaction (1.4 ± 1.7) of the long UL was 1.0 higher (F[1, 211] = 18.23, $p < 0.001$) compared to that (0.4 ± 1.7) of the short UL. The overall satisfaction (1.0 ± 1.6) of the short MCD was 0.4 higher (F[1, 211] = 5.85, $p = 0.02$) compared to that (0.7 ± 2.0) of the long MCD.

DISCUSSION

The present study identified main design factors of vacuum cleaner handles of which shapes are complicated. Vacuum cleaner handle design factors were analyzed in terms of length, distance, angle, and curvature by analyzing six different handle shapes of existing vacuum cleaners. Upper part length (UL), midpoint-pipe centerline distance (MCD), tilt angle (TA), and cross-section upper part curvature radius (UR) of handle were determined as the main design factors of vacuum cleaner handles through comprehensive consideration of importance evaluation result and vacuum handle design expert opinions.

In the study, design factor properties of vacuum cleaner handles were obtained through an ergonomic evaluation of the six vacuum cleaner handles in terms of motion, muscular effort, and satisfaction in vacuuming motion. The CROM deviation of the small TA (40.6° ~ 46.6°) was 1.8% higher in abduction/adduction of shoulder, 2.6% lower in flexion/extension of shoulder, 1.6% lower in ulnar/radial deviation of wrist compared to that of large TA (56.6°~ 64.7°). Next, % MVC < 5% of small UR (4.9 ~ 13.3 mm) was 1.7% higher in deltoid, 3.0% higher in FCR compared to that of large UR (17.8 ~ 19.9 mm). Significantly higher satisfaction levels were found in the long UL (118.4 mm ~ 154.8 mm) compared to the short UL (68.7 mm ~ 98.2 mm), the short MCD (3.0 mm ~ 25.8 mm) compared to the long MCD (39.4 mm ~ 78.4 mm) of vacuum cleaner handles. Overall satisfactions were found significantly higher in the long UL and short MCD of vacuum handle. The results of this study can be utilized to develop ergonomic handles of vacuum cleaners.

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