

Development of a usability evaluation method using natural product-use motion

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Abstract

The present study developed and tested a new usability evaluation method which considers natural product-use motions. The proposed method measures both natural product-use motions (NMs) and actual product-use motions (AMs) for a product using an optical motion capture system and examines the usability of the product based on motion similarity (MS; %) between NMs and AMs. The proposed method was applied to a usability test of four vacuum cleaners (A, B, C, and D) with 15 participants and their MSs were compared with EMG measurements and subjective discomfort ratings. Cleaners A (44.6%) and C (44.2%) showed higher MSs than cleaners B (42.9%) and D (41.7%); the MSs mostly corresponded to the EMG measurements, which could indicate that AMs deviated from NMs may increase muscular efforts. However, the MSs were slightly different from the corresponding discomfort ratings. The proposed method demonstrated its usefulness in usability testing, but further research is needed with various products to generalize its effectiveness.

Keywords: Natural product-use motion; Motion similarity; Usability evaluation

1 Introduction

Ergonomic analysis of product-use posture and motion plays a key role to improve the usability of a product. Product-use posture and motion influence users' satisfaction as well as task efficiency during physical interactions ([Clamann et al., 2012](#)). In general, product-use posture and motion are highly affected by the physical design factors (e.g. length, height, and weight) of a product. Thus, the product design based on the ergonomic relationships between users and a product under consideration may help users have more comfortable and convenient physical interactions with a product ([Fostervold et al., 2006](#); [Rempel and Horie, 1994](#); [Rose, 1991](#); [Smith et al., 1998](#); [Qin et al., 2013](#)). For example, [Rempel et al. \(2007\)](#) analyzed wrist and forearm postures while keyboarding at various keyboard angles, and found the optimal split (12°) and gable (14°) angles which could reduce the awkward motions of the wrist and forearm.

Most studies analyzing product-use posture and motion focused on the biomechanical load and motion efficiency while users interact with products. Nelson et al. (2000) measured keyboarding motions by an opto-electric finger monitor and analyzed finger/wrist postures and motions based on tendon excursion, angular velocity, and angular acceleration. [Moffet et al. \(2002\)](#) measured wrist postures while a laptop was used on the knees or table with a three-dimensional video system and quantified the deviation of wrist posture from the neutral wrist posture. [Morag et al. \(2005\)](#) measured shoulder, elbow, and wrist postures while operating a trackball at a standing posture using video cameras and identified uncomfortable postures (>30° deviation from the neutral posture). [Moore et al. \(2014\)](#) investigated upper body motions while wearing a spacesuit using an optical motion capture system with eight cameras to evaluate the compatibility between the spacesuit and the upper body movements. [Lu et al. \(2016\)](#) measured ingress and egress motions for the

rear seat of minivans using an optical motion capture system and developed eight motion strategies for ingress and egress to propose the ergonomic door designs for minivans.

A few studies have analyzed natural product-use posture and motion which are determined by user preference and used the natural motion information as a reference to evaluate physical interactions between users and a product. This is because using a product with natural product-use posture and motion could increase the affordance of a product and the user satisfaction of the product (Chang, 2007). In addition, finding natural product-use posture and motion could provide a better understanding to improve the physical usability of a product. Nyberg and Kempic (2006) demonstrated the usefulness of this approach by examining users' natural drum washer-use motions; they found design directions to improve the physical interactions between users and a drum washer. However, existing studies on natural product-use posture and motion are limited for their qualitative approach in analysis (Allie et al., 1999; Nyberg and Kempic, 2006).

The present study defined natural product-use motion (NM) and developed a usability evaluation method based on quantitative measurement of NM. The usefulness of the proposed method in the study was investigated in usability evaluation of four canister-type vacuum cleaners having different design specifications. Also, the motion analysis results were compared with those of EMG and subjective discomfort to identify their association with muscular efforts and user satisfaction.

2 Usability evaluation method using natural product-use motion

2.1 Conceptual definition of natural product-use motion

It is assumed that all users have natural product-use motions (NMs) which they prefer in operating a product under consideration. In other words, the NMs can be considered as a user-preferred product-use motion for the product. The following three conditions were additionally assumed to the concept of NM for a product under consideration: (1) users already recognize the purpose of the product; (2) users already experienced how to use the product; and (3) users can determine their NMs.

2.2 Development of a usability evaluation method using NM

The usability evaluation method proposed in the present study consists of three major steps (Fig. 1): (1) product characteristic analysis; (2) motion measurement; and (3) usability analysis. First, the product characteristic analysis identified the design characteristics, user characteristics, environment characteristics, and task characteristics of a product, which can affect users' posture and motion while using the product (Chang and You, 2006; HFES300 Committee, 2004). As for design characteristics, the dimensions (e.g. size, weight, shape) of the product are measured. As for user characteristics, user profiles (e.g. age, gender, and anthropometric attributes) and user requirements (e.g. explicit or implicit needs of users or design requirements for design problems perceived) are obtained through a user survey or a focus group interview. As for environment characteristics, use environments and their conditions such as floor materials, floor smoothness, and ambient temperature are identified. Lastly, as for task characteristics, major tasks and subsidiary tasks with the product are analyzed.

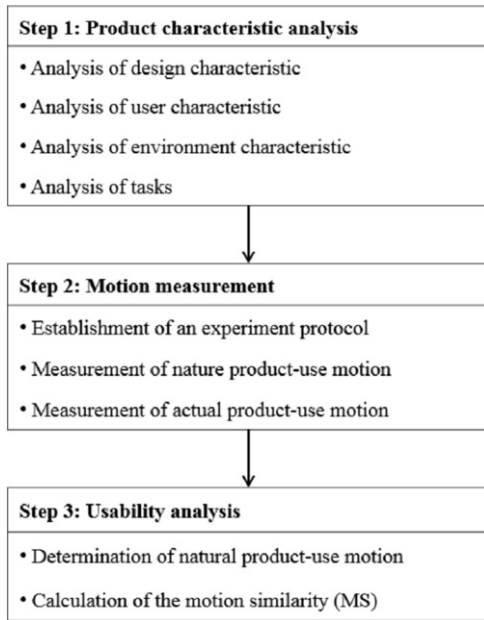


Fig. 1 Usability evaluation process using natural product-use motion.

alt-text: Fig. 1

In the second step, an experimental protocol including measurement of both NMs and actual product-use motions (AMs) is planned. An experimental protocol is established based on product characteristics identified in the previous step; for example, participants can be selected using the user characteristics of the target product. Also, experimental tasks are designed by referring to the environment and task characteristics of the product. The NMs and AMs about the product are recorded using a motion capture system. Note that the NMs are users' voluntary motions (under the purpose of the product-use) when the product is not given. Meanwhile, the AMs are ordinary product-use motions while operating the product, so they are affected by the physical design of the product.

In the last step, the usability of the target product is evaluated by the motion similarity (MS; unit: %) between NMs and AMs. The NMs and AMs are operationally defined in the present study as the form of the range of motion (ROM) based on the average of 5th (lower bound) and 95th (upper bound) percentiles on each participant's ROMs because 90% accommodation of the target population is commonly employed in anthropometric studies (HFES300 Committee, 2004; Jung et al., 2009, 2010; Kwon et al., 2009). MS is defined as the ratio of AMs spent in the range of NMs as shown in Fig. 2 and Equation (1), where T is the total time of AMs, T_{in} is the time of AMs in the range of NMs, and MS is the proportion of T_{in} to T . For example, out 30 s of canister AMs, 24 s of canister AMs is in the range of corresponding NMs, its MS becomes 80% (= 24/30). Consequently, MS can be served as a usability index of the target product since it quantifies the similarity between ordinary product-use motion and natural product-use motion.

$$MS(\%) = \frac{T_{in}}{T} \times 100 \quad (1)$$

where:

T_{in} = time of actual product-use motion in the range of natural product-use motion

T = total time of actual product-use motion

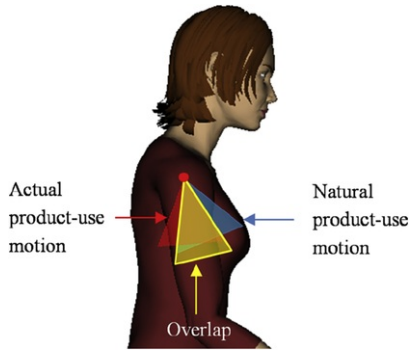


Fig. 2 Motion similarity between natural and actual product-use motions.

alt-text: Fig. 2

3 Case study: canister-type vacuum cleaner

The usefulness of the proposed method was tested in usability evaluation of four canister-type vacuum cleaners the design specifications of which were shown in [Table 1](#).

Table 1 Design specifications of four canister-type vacuum cleaners.

alt-text: Table 1

Dimension	Cleaner			
	A	B	C	D
Canister length range (cm)	82 to 93	88 to 100	90 to 107	97 to 120
Canister weight (kg)	1.15	1.39	1.52	1.89
Brush weight (kg)	0.26	0.31	0.41	0.64

3.1 Product characteristic analysis

The design, user, environment, and task characteristics of the vacuum cleaners were analyzed. First, the design characteristics of the four vacuum cleaners were identified by investigating each user's manual and measuring key dimensions such as canister weight and length range highly related to vacuum cleaner-use motions. Next, user characteristics were investigated through a user survey. A usability questionnaire was distributed to 250 users who were familiar with use of canister-type vacuum cleaner and 92 of them were collected (response rate = 37%). The vacuum cleaner usability survey showed that female homemakers in 30's to 50's are the major user group (73%) and most of the users finish vacuum cleaning time within 30 min (73%). It also revealed that the users often feel discomfort on the neck, elbow, wrist, and lower back while using current canister-type vacuum cleaners. Then, the environment characteristics of vacuum cleaner were investigated by analyzing videos which were recorded with five female homemakers while they cleaned their home. Lastly, a task analysis was conducted analyzing the videos and user's manuals of vacuum cleaner.

3.2 Experimental protocol

3.2.1 Participants

Fifteen female homemakers in 30s-50s were recruited in the experiment. Their average age and height were 38 years (SD = 5.0) and 159.5 cm (SD = 4.8), respectively. All were well-experienced in use of canister-type vacuum cleaners. Also, they were all right-handed, and did not have any musculoskeletal discomfort or disorder. All participants signed an informed consent form and their participation was compensated.

3.2.2 Motion measurement

Falcon 240 (Motion Analysis Co., USA), an optical 3D motion capture system, was employed for motion measurement. The experiment space of 1.8 m (length) × 3 m (width) was set up for motion capturing and a thin floor material was installed on the floor by referring to the environment characteristics of vacuum cleaners. Five motion capture cameras (sampling rate = 50 Hz) surrounded the experiment space and 22 optical markers (diameter = 2.5 cm; Fig. 3) were placed on the participant to track motions of the neck, right shoulder, right elbow, right wrist, lower back, and knees; these joints were determined based on the user characteristics. EVaRT 5.0 (Motion Analysis co., USA) was used to edit captured motion data and joint angles were extracted by Solver Interface 2.9 (Motion Analysis co., USA).

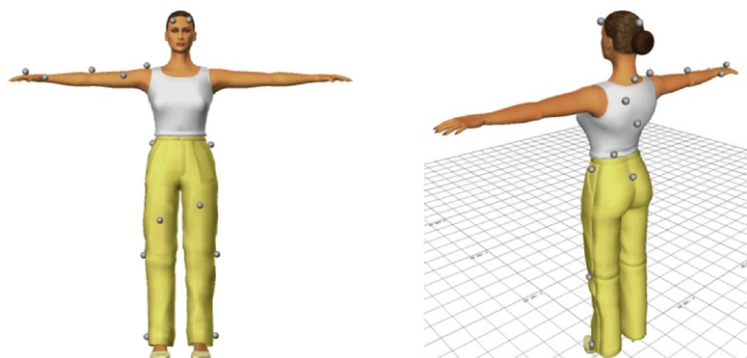


Fig. 3 An optical marker set for whole body motion analysis.

alt-text: Fig. 3

3.2.3 EMG measurement and processing

EMG signals were collected using a Telemyo 900 electromyography system (Noraxon Inc, USA) from major muscles of the arm, shoulder, and lower back for operation of canister in vacuum cleaning task. Electrodes were attached to the skin areas of four muscles (brachioradialis, extensor carpi ulnaris, deltoid, and erector spinae) by following the anatomical guide by Perotto (1994). Surface EMG signals were measured at 1000 Hz and filtered by a finite impulse response filter to remove noises less than 10 Hz or higher than 350 Hz. Then, RMS values of filtered EMG signals in moving window of 50 ms were obtained and their average EMG values were calculated (Kumar and Mital, 1996; Lowe et al., 2001).

3.2.4 Subjective discomfort rating

Subjective discomfort ratings were measured using the Borg CR-10 scale ('0' for no discomfort and '10' for extreme discomfort) (Borg, 1998). Participants were asked to rate their discomfort level at the neck, shoulder, elbow, wrist, lower back, knees, and whole body. Subjective discomfort ratings were obtained after each AM measurement.

3.2.5 Experimental protocol

Motion capture experiments were conducted in four phases: (1) orientation; (2) preparation; (3) practice; and (4) main experiment. In the first phase, the purpose and procedure of the experiment were explained to the participants and basic terms and concepts such as NM and AM were explained. In the second phase, the participants wore a motion capture suit and the markers were attached at the pre-determined locations (Fig. 3). In the third phase, a 10-min exercise was provided for the participant to help not only be familiarized to the experiment but also find her natural vacuum cleaner-use motions. In the last phase, NMs and AMs were recorded separately for 30 s. The four vacuum cleaners were used for recording AMs in random order; the participants were allowed to adjust the canister lengths before AM measurement. Meanwhile, no vacuum cleaner was given to the participant in recording NMs. All measurements were repeated three times. Thus, a total of 125 measurements ($NM \times 3 \text{ repetitions} + 4 \text{ cleaners} \times AMs \times 3 \text{ repetitions}$) were collected for each participant in the case study. EMG measurements were collected simultaneously with AM measurements. Lastly, subjective discomfort ratings were measured to investigate the association with MS after the AMs of each cleaner.

The locations of the feet and directions of cleaning were controlled during the experiment as shown in Fig. 4. The distance between the feet and the angle of the feet were fixed to 25 cm with 40°, respectively, based on the results of a preliminary experiment regarding feet distance (25 ± 4.2 cm) and feet angle ($40^\circ \pm 7.3^\circ$) which were conducted before the case study with three participants. The cleaning directions were controlled to five levels (0°, 45°, 90°, 135°, and 180°) by using marks on the floor and the speed of the arm swing for cleaning (40 arm swings/min) was controlled using a metronome.

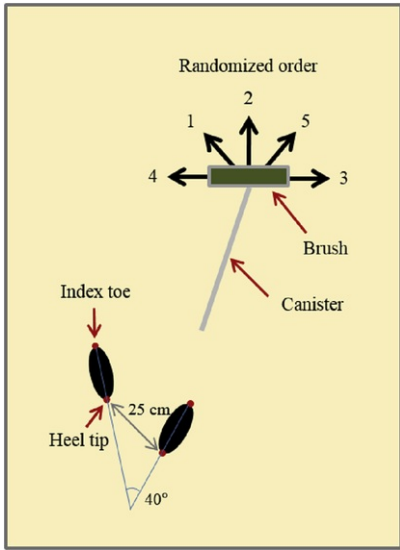


Fig. 4 Foot locations and swiveling directions for cleaning task.

alt-text: Fig. 4

3.2.6 Reliability assessment on NM

To assess the reliability of NM within an individual participant and the reliability of NM between participants, the standard deviation of measurement error (SD_{me}) and the standard deviation of biological variation (SD_{bv}) were calculated by Equations (2) and (3) (Norkin and White, 2009).

$$SD_{me} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{k - 1}} \quad (2)$$

where:

x_i = i th measurement for an individual

\bar{x} = mean of measurements for an individual

k = number of measurements for an individual

$$SD_{bv} = \sqrt{\frac{\sum (\bar{x}_j - \bar{X})^2}{n - 1}} \quad (3)$$

where:

\bar{x}_j = mean of j th participant

\bar{X} = mean of measurements for all participants

n = number of participants

3.3 Results

3.3.1 Quantified NM and its reliability

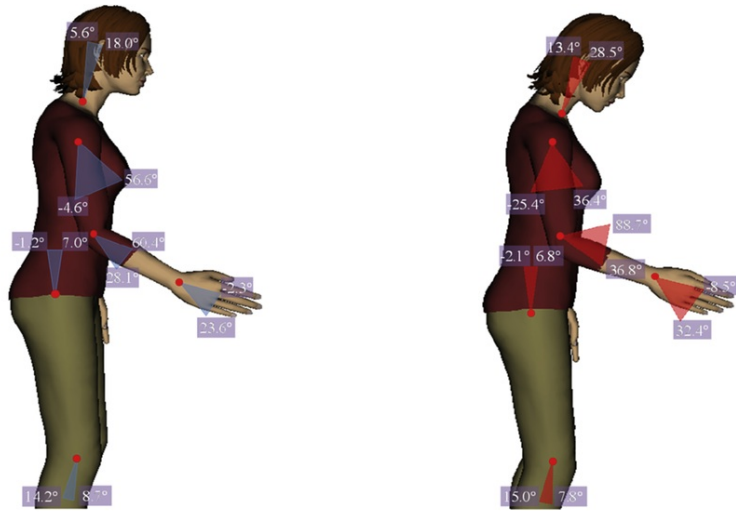
NMs were defined quantitatively using 5th (lower limit) and 95th (upper limit) percentiles of its ROMs (explained in section 2.2). The intervals of NM were relatively large at the upper limb (right shoulder, elbow, and wrist; Table 2). Most of movements (related to swings) of the upper limb took place in front of the body and only a little extension of the shoulder was observed (Fig. 5a). On the other hand, the intervals of NM at the lower back, neck, and knees were small. The upper body slightly leaned forward (the neck flexed between 5.6° and 18.0° and the lower back flexed between -1.2° and 7.0°), and the lower limbs had extremely small movements (the knees flexed between 8.2° and 14.2°).

Table 2 The intervals of natural vacuum cleaner-use motions and their SD_{me} and SD_{bv} (unit: °).^a

alt-text: Table 2

Joint	Motion	Average boundary of NM			SD_{me}		SD_{bv}	
		LL	UL	Interval	LL	UL	LL	UL
Neck	Flexion(+)/extension(-)	5.6	18.0	12.4	2.7	1.5	12.4	10.1
	Left(+)/right lateral flexion(-)	-35.7	2.6	38.3	1.9	3.7	14.7	12.9
	Left(+)/right(-) rotation	-26.6	-13.8	12.8	1.0	1.9	11.4	11.6
Shoulder	Elevation(+)/extension(-)	-4.6	56.6	61.3	4.1	4.8	21.9	26.8
	Lateral(+)/medial rotation(-)	-17.0	27.6	44.7	3.0	2.8	17.3	21.2
	Adduction(+)/abduction(-)	7.0	55.3	48.3	7.0	2.1	22.0	31.1
Elbow	Flexion(+)	28.1	60.4	32.2	1.7	3.3	7.9	20.2
Wrist	Flexion(+)/extension(-)	-11.0	20.8	31.8	7.0	2.5	16.7	11.7
	Supination(+)/pronation(-)	5.5	42.9	37.4	4.9	4.4	13.6	15.1
	Ulnar(+)/radial(-) deviation	-2.3	23.6	25.9	4.0	11.2	16.4	12.9
Lower back	Flexion(+)/extension(-)	-1.2	7.0	8.2	2.3	2.7	12.3	15.7
	Left(+)/right(-) lateral flexion	-7.2	-0.2	7.0	1.1	1.3	9.5	11.1
	Left(+)/right(-) rotation	-17.3	-6.5	10.8	2.3	2.5	10.9	16.1
Right knee	Flexion(+)	8.7	14.2	5.6	1.8	1.2	4.4	5.4
Left knee	Flexion(+)	7.7	14.1	6.4	1.3	1.6	4.2	7.1

^a LL: lower limit (5th percentile), UL: upper limit (95th percentile).



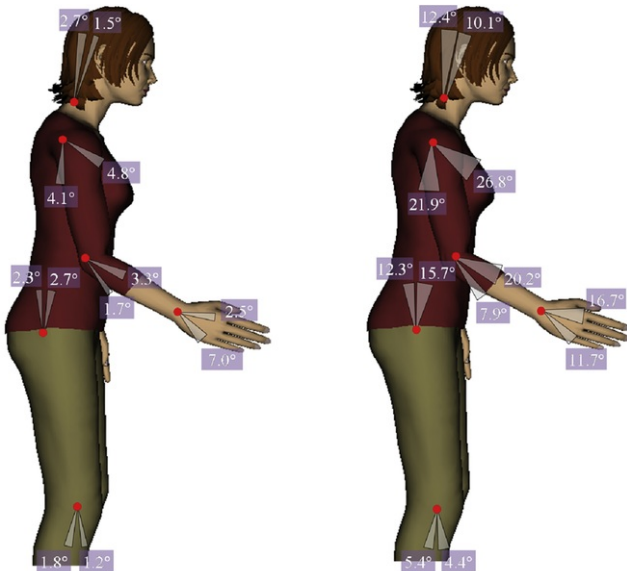
(a) Natural cleaner-use motion

(b) Actual cleaner-use motion

Fig. 5 Natural and actual vacuum cleaner-use motions at the wrist, elbow, shoulder, neck, lower back, and knee.

alt-text: Fig. 5

To evaluate the reliability of NM, $SDme$ within each participant and $SDbv$ among all participants were analyzed (Table 2). The $SDme$ and $SDbv$ were computed on both lower limits (LL) and upper limits (UL) of NMs on each body joint. The results presented that average $SDme$ was 3.1° (Fig. 6) but $SDbv$ was relatively large (13.2°) except the knees (5.3°). Also, larger standard deviations were found at the joints (e.g., shoulder) with larger movements during cleaner swings ($SDme: r = 0.45, p = 0.012; SDbv: r = 0.78, p < 0.001$).



(a) Measurement error ($SDme$)

(b) Biological variation ($SDbv$)

Fig. 6 Repeatability for the lower and upper limits of natural vacuum cleaner-use motions.

alt-text: Fig. 6

3.3.2 Quantified AM

The AMs of the four vacuum cleaners were also quantified based on 5th (lower limit) and 95th (upper limit) percentiles of its ROMs. The AMs had the following different motion features from the NMs. First, the AMs had larger movements than the NMs across all the joints (Table 3); especially, relatively larger differences in the interval (LL to UL) were observed at the wrist (NM: 31.7°, AM: 50.1°) and elbow motions (NM: 32.2°, AM: 51.9°). Second, more flexed neck motions were found in the AMs (13.4°-28.5°) than the NMs (5.6°-18.0°), but their lower back motions were similar to those of the NMs (Fig. 5b). Third, the shoulder showed different swing motions in the AMs from the NMs; it moved clearly back and forth beside the body (-25.4°-36.4°). In comparison with the NMs (-4.6°-56.6°), the shoulder motions of the AMs had larger extensions/smaller elevations (back and forth) and larger medial rotations/smaller lateral rotations, while the movement intervals of the shoulder motions were very similar to one another (NM: 44.7°-61.3°, AM: 44.4°-68.5°). On the other hand, small movements were found at the knees (left: 7.1°, right: 9.4°).

Table 3 The intervals of actual vacuum cleaner-use motions (unit: °).

alt-text: Table 3

Joint	Motion	Cleaner A			Cleaner B			Cleaner C			Cleaner D		
		LL	UL	Interval	LL	UL	Interval	LL	UL	Interval	LL	UL	Interval
Neck	Flexion(+)/extension(-)	10.9 (SE: 3.0)	26.8 (1.2)	15.9	13.8 (2.6)	29.0 (1.2)	15.2	15.2 (3.0)	29.0 (1.3)	13.8	13.6 (1.9)	29.2 (0.9)	15.6
	Left(+)/right lateral flexion(-)	-32.7 (3.5)	10.9 (2.9)	43.6	-25.4 (3.8)	18.0 (3.4)	43.4	-26.9 (3.5)	17.3 (3.8)	44.2	-23.7 (3.1)	20.7 (3.5)	44.4
	Left(+)/right(-) rotation	-32.1 (1.9)	-17.6 (1.9)	14.4	-29.6 (1.6)	-15.2 (1.7)	14.3	-29.3 (1.5)	-15.9 (1.6)	13.4	-31.5 (1.8)	-15.9 (1.7)	15.5
Shoulder	Elevation(+)/extension(-)	-20.0 (4.8)	37.7 (6.5)	57.8	-26.6 (5.1)	34.0 (4.8)	60.6	-24.5 (4.8)	35.7 (4.7)	60.2	-30.4 (4.6)	38.1 (4.4)	68.5
	Lateral(+)/medial rotation(-)	-32.5 (4.2)	14.7 (5.7)	47.3	-34.8 (3.9)	9.9 (6.0)	44.6	-35.0 (4.1)	9.4 (5.4)	44.4	-39.8 (3.8)	9.4 (4.2)	49.2
	Adduction(+)/abduction(-)	-3.4 (4.4)	46.2 (4.6)	49.6	-2.1 (3.3)	44.7 (3.5)	46.8	-2.3 (3.3)	43.9 (3.8)	46.3	-14.8 (3.3)	45.3 (4.0)	60.2
Elbow	Flexion(+)	32.8 (1.8)	82.7 (2.7)	49.9	37.4 (1.9)	89.4 (3.1)	52.0	36.2 (2.1)	86.6 (3.6)	50.4	40.9 (2.3)	96.0 (3.1)	55.1
Wrist	Flexion(+)/extension(-)	-12.6 (3.5)	27.6 (2.3)	40.2	-8.2 (3.7)	35.6 (3.7)	43.8	-3.4 (2.9)	34.2 (3.1)	37.6	-9.7 (3.3)	32.1 (2.6)	41.8
	Supination(+)/pronation(-)	-9.0 (2.4)	44.0 (2.8)	53.0	-6.3 (2.6)	42.6 (2.6)	48.9	-10.0 (2.3)	45.4 (3.2)	55.4	-11.0 (2.8)	49.2 (2.8)	60.3
	Ulnar(+)/radial(-) deviation	-12.2 (6.0)	45.3 (2.3)	57.5	-7.5 (4.8)	43.0 (2.3)	50.6	-6.4 (5.2)	44.8 (2.3)	51.1	-11.9 (5.9)	48.9 (2.6)	60.9
Lower back	Flexion(+)/extension(-)	-3.1 (2.0)	6.1 (2.0)	9.2	-2.0 (1.3)	5.5 (1.8)	7.5	-2.5 (1.6)	4.7 (1.7)	7.3	-0.8 (1.8)	10.9 (2.8)	11.7
	Left(+)/right(-) lateral flexion	-8.6 (0.9)	-1.0 (1.0)	7.5	-8.0 (1.0)	0.1 (0.9)	8.1	-7.9 (0.8)	-0.3 (0.9)	7.7	-7.8 (1.2)	1.8 (1.1)	9.6

	Left(+)/right(-) rotation	-18.4 (3.2)	-3.7 (1.8)	14.0	-13.6 (2.9)	-1.5 (1.4)	12.0	-12. (2.8)	-1.2 (1.5)	11.2	-16.4 (2.8)	-1.3 (1.3)	15.0
Right knee	Flexion(+)	7.9 (1.3)	14.5 (1.4)	6.6	7.7 (1.4)	14.1 (1.2)	6.4	8.0 (1.3)	14.3 (1.4)	6.2	7.7 (1.0)	16.9 (1.1)	9.2
Left knee	Flexion(+)	6.9 (1.2)	15.5 (1.9)	8.7	6.0 (1.2)	15.8 (1.5)	9.8	6.2 (1.1)	14.6 (1.6)	8.5	6.2 (1.1)	16.6 (1.5)	10.4

3.3.3 Motion similarity (MS)

MS (unit: %) between NM and AM was computed as the ratio of AM spent in the range of NM; [Table 4](#) and [Fig. 7](#) showed the average MSs of all the participants for each cleaner. The motions of the shoulder, wrist, and lower back showed relatively higher MSs than the other joints; especially, the shoulder elevation/extension had more than 60% MSs for all the cleaners, and MSs at the shoulder adduction/abduction and the lower back flexion/extension were close to 70%. Meanwhile, the neck, elbow, and knee motions showed relatively lower MSs (20%-40%); especially, the neck motions except left/right lateral flexion had less than 30% MSs.

Table 4 Motion similarity between natural and actual vacuum cleaner-use motions (unit: %).^a

alt-text: Table 4

Joint	Motion	Cleaner				F-value	p-value
		A	B	C	D		
Neck	Flexion/extension	26.3 (SE: 6.7)	26.6 (7.1)	29.8 (8.2)	35.8 (6.6)	2.03	0.124
	Left/right lateral flexion	53.6 (5.1) ^H	38.8 (5.3) ^L	43.8 (5.1) ^L	36.7 (5.7) ^L	4.99	0.005
	Left/right rotation	29.0 (7.4)	22.6 (6.4)	24.4 (7.0)	27.2 (7.0)	1.46	0.238
Shoulder	Elevation/extension	66.3 (5.1) ^H	60.0 (5.7) ^L	61.6 (5.3) ^{H, L}	60.9 (4.3) ^{H, L}	3.23	0.032
	Lateral/medial rotation	36.7 (5.6)	30.8 (5.4)	33.4 (6.3)	28.7 (4.6)	2.2	0.103
	Adduction/abduction	71.4 (5.3)	71.7 (5.3)	72.5 (5.8)	67.1 (4.9)	1.73	0.175
Elbow	Flexion	47.4 (4.6) ^H	34.4 (5.5) ^M	35.7 (5.9) ^M	26.2 (5.3) ^L	18.49	<0.0001
Wrist	Flexion/extension	41.9 (7.1)	42.4 (6.8)	46.4 (7.5)	47.5 (6.6)	1.93	0.139
	Supination/pronation	51.4 (5.0)	50.9 (5.3)	53.0 (5.5)	46.1 (5.0)	0.92	0.439
	Ulnar/radial deviation	41.6 (4.3)	47.0 (3.5)	44.4 (3.8)	43.0 (2.7)	1.35	0.273
Lower back	Flexion/extension	64.4 (7.6) ^H	71.7 (6.4) ^H	71.3 (6.4) ^H	58.5 (8.6) ^H	2.85	0.049
	Left/right lateral flexion	46.6 (7.3) ^L	54.2 (7.2) ^{H, L}	60.6 (6.3) ^H	44.0 (5.5) ^L	5.26	0.004
	Left/right rotation	29.9 (6.9) ^{H, L}	23.7 (6.3) ^{H, L}	21.2 (5.4) ^L	35.9 (6.5) ^H	3.09	0.037
Right knee	Flexion	25.8 (6.3)	31.2 (8.0)	29.0 (7.6)	30.5 (5.6)	0.47	0.704
Left knee	Flexion	36.8 (8.5)	37.1 (6.4)	35.2 (7.0)	36.7 (7.9)	0.07	0.976
Average MS score		44.6	42.9	44.2	41.7		
Average rank (the lower, the better)		2.4	2.5	2.2	2.9		
The number of the joint motions more than a 60% MS score		3	3	4	2		

^a Relatively high motion similarity (>60%) were shaded. Superscript letters indicate significant differences at $\alpha = 0.05$: L < M < H.

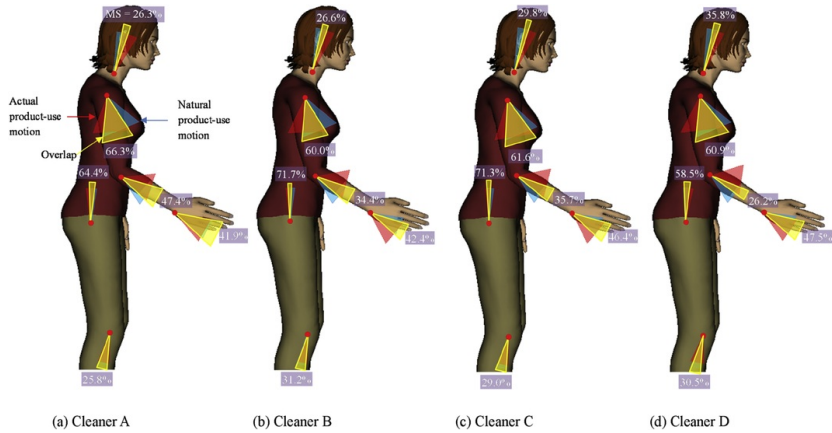


Fig. 7 Motion similarity (%) between natural and actual vacuum cleaner-use motions.

alt-text: Fig. 7

Overall, cleaners C and A presented higher MSs than cleaners B and D across all of the joints (Table 4). Cleaner C had a better MS rank (average = 2.2) among the four cleaners; in particular, cleaner C's strengths were at the motions of the shoulder, elbow, and wrist, and it also had the highest number of joint motions (= four) which showed more than a 60% MS. Cleaner A presented high MSs (average 44.6%) and an average of 2.4 MS rank, which were similar to cleaner C (44.2% and 2.2 rank). On the other hand, cleaners B (average 2.5 rank) and D (average 2.9 rank) were ranked third and last among the cleaners. The average MSs of cleaners B and D were 42.9% and 41.7%, respectively, and the number of joint motions showing more than a 60% MS was only two for cleaner B and three for cleaner D.

3.3.4 Relationship between MSs and design specifications

The relationships between MSs and design specifications of the four vacuum cleaners (Fig. 8) were analyzed to identify how a design specification affects MS. First, the relationship between MSs and design specifications were analyzed at the shoulder, elbow, and wrist motions, which were most used joints in use of cleaners. One-way within subject ANOVA test with $\alpha = 0.05$ showed that MS varied significantly at the shoulder elevation/extension ($F(3, 42) = 3.23, p = 0.032$) and elbow flexion ($F(3, 42) = 18.49, p < 0.0001$) as canister length and weight increased; both the length and weight of the canisters increased together from cleaners A to D. The trend of MS at the shoulder elevation/extension was close to a Ladle-shape (Fig. 8a), and the Student-Newman-Keuls (SNK) test showed that cleaners A, C, D and cleaners B, C, D had statistically the higher and lower groups respectively. Also, MSs at the elbow flexion declined significantly from cleaner A to D; cleaners B and C were categorized statistically into a same middle group (Table 4). On the other hand, MSs at the wrist joint motions did not have any significance when the canister length and weight increased.

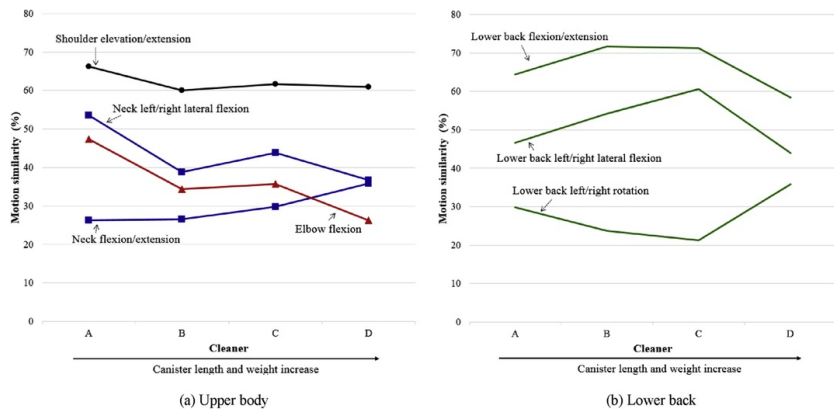


Fig. 8 Relationship between motion similarities and design specifications at statistically significant joint motions.

alt-text: Fig. 8

Next, the relationship between MSs and design specifications were analyzed at the neck, lower back, and knee motions with relatively smaller movements while using the cleaners. The MSs of the following four joints motions were statistically significant when the canister length and weight increased from cleaner A to D (Table 4): (1) the neck left/right lateral flexion ($F(3, 42) = 3.09, p = 0.037$), (2) the lower back flexion/extension ($F(3, 42) = 2.85, p = 0.049$), (3) the lower back left/right lateral flexion ($F(3, 42) = 5.26, p = 0.004$), and (4) the lower back left/right rotation ($F(3, 42) = 3.09, p = 0.037$). First, the MSs at the neck left/right lateral flexion had a negative relationship with canister length and weight. The SNK test classified statistically cleaners B, C, and D into a lower group. Second, the MSs showed reverse U-shapes at the lower back flexion/extension and left/right lateral flexion (Fig. 8). Although the SNK test grouped all the cleaners into the same group at the lower back flexion/extension, cleaners B and C showed relatively higher MSs than cleaners A and D at both the joint motions. Third, the trend of the MSs at the lower back left/right rotation showed a completely different shape from those of the other lower back motions. It had a clear U-shape, and statistically the lowest MS was observed in cleaner C. On the other hand, another remarkable increase was found at the neck flexion/extension as shown in Fig. 8, but the MSs failed to show statistical significance when the canister length and weight increased. Lastly, the trend of the MSs at the knee joint motions was observed, but did not show any statistical significance among the vacuum cleaners.

3.3.5 Average EMG measurement

EMG measurement was conducted to identify whether MS is associated with muscle activity. To rank cleaners A, B, C, and D in terms of muscular efforts, average EMG (mV) measurements were collected on the deltoid anterior, brachioradialis, extensor carpi ulnaris, and erector spine which were related to shoulder elevation, elbow flexion, ulnar deviation and wrist extension, and lower back extension, respectively (Perotto, 1994).

Overall, cleaners B and D had relatively higher average EMG values than cleaners A and C except the erector spine (Fig. 9). A one-way within subject ANOVA test at $\alpha = 0.05$ determined that all the average EMG values among the cleaners were statistically significant at the four muscles: (1) deltoid: $F(3, 42) = 11.71, p < 0.0001$, (2) brachioradialis: $F(3, 42) = 18.24, p < 0.0001$, (3) extensor carpi ulnaris: $F(3, 42) = 9.11, p < 0.0001$, and (4) the erector spine: $F(3, 42) = 3.34, p = 0.028$. Also, the SNK test classified cleaner D into a statistically higher group and categorized cleaners A and C into a statistically lower group across all the muscles.

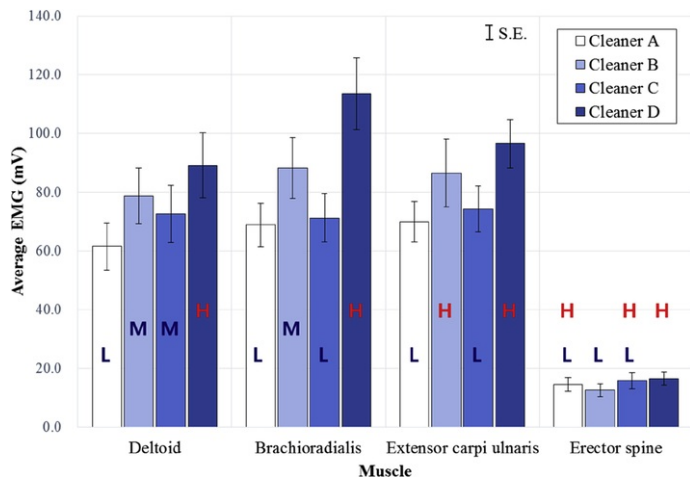


Fig. 9 Average EMG values among vacuum cleaners at four muscles (alphabet letters indicate significant differences at $\alpha = 0.05$: L < M < H).

alt-text: Fig. 9

The comprehensive trends of the MSs corresponded to EMG measurements. Most EMG results highly correlated with MSs. In particular, the deltoid and brachioradialis showed very similar patterns between the MSs and EMG results; cleaners A and C had higher MS scores and lower average EMG values, while cleaners B and D had lower MS scores and higher average EMG values. On the other hand, although the erector spine showed somewhat different ranking patterns from the MSs (the results of cleaners A and C were reversed), they shared similar trends overall. However, the extensor carpi ulnaris failed to show any similar pattern to the MS at the wrist ulnar deviation and extension.

3.3.6 Subjective discomfort rating

The relationship between MS and user satisfaction was investigated through the results of subjective discomfort rating. Across all the discomfort ratings, cleaner D had the highest discomfort ratings, and cleaners A, B, and C followed in order (Table 5). A one-way within subject ANOVA test with $\alpha = 0.05$ showed that the subjective discomfort ratings among the cleaners were statistically significant across all the joints as well as at the whole body. Also, across all the discomfort ratings, the SNK test categorized cleaner D into a statistically higher group and classified cleaners A, B, and C into a statistically lower group. In sum, overall, the subjective discomfort ratings showed somewhat different patterns from the MSs except for a few motions (the lower back flexion/extension, left/right lateral flexion, and the neck flexion/extension).

Table 5 Subjective discomfort ratings (Borg CR-10) of cleaners.^a

alt-text: Table 5

Joint	Cleaner				F-value	p-value
	A	B	C	D		
Whole body	3.0 (SE: 0.6) ^L	1.8 (0.5) ^L	1.4 (0.4) ^L	6.1 (0.7) ^H	14.56	<0.0001
Neck	1.2 (0.4) ^{H,L}	0.6 (0.2) ^L	0.6 (0.2) ^L	2.3 (0.5) ^H	5.44	0.003
Shoulder	2.8 (0.5) ^L	1.1 (0.3) ^L	1.4 (0.4) ^L	5.1 (0.8) ^H	16.20	<0.0001
Elbow	2.7 (0.6) ^L	1.7 (0.5) ^L	1.8 (0.5) ^L	5.2 (0.6) ^H	13.56	<0.0001
Wrist	3.7 (0.6) ^L	2.9 (0.5) ^L	2.9 (0.7) ^L	6.7 (0.6) ^H	10.01	<0.0001
Lower back	2.2 (0.6) ^L	1.4 (0.4) ^L	1.3 (0.4) ^L	3.1 (0.7) ^H	3.31	0.029

Right knee	1.5 (0.5) ^{H,L}	1.3 (0.4) ^{H,L}	1.2 (0.4) ^L	2.8 (0.6) ^H	3.01	0.041
Left knee	1.3 (0.5) ^L	1.1 (0.5) ^L	0.9 (0.3) ^L	2.9 (0.7) ^H	3.63	0.021

^a Superscript letters indicate significant differences at $\alpha = 0.05$: L < H.

4 Discussion

4.1 Significance of the proposed method

The proposed usability evaluation method in this study conceptually defined NM from the user point of view. The concept of NM was clarified in terms of the characteristics of product-use and defined based on user-profiles. In other words, the concept of NM was not only specified with the contextual requirements including product design characteristics (e.g. product sizes and shapes), user characteristics (e.g. user profiles and user requirements), environment characteristics (e.g. product-use environment and the conditions), and task characteristics (e.g. major and minor tasks), but also defined based on the purpose of product-use, user-experience, and user-intention.

A quantitative measurement method of NM and AM was proposed in the present study. The proposed measurement method consists of a series of actions: (1) NM is determined by a participant and is captured by a motion capture system while a product under consideration is not provided; (2) AM is measured by a motion capture system while the product is provided to the participant; (3) NM and AM are defined quantitatively using the range of motion at each joint and motion. Two technological advantages of the proposed method are expected: (1) the series of actions in the method may allow easy access to the measurement system and help measure systematically NM and AM, regardless of how much of experience users have on motion studies, and (2) the proposed method allows the direct comparisons between NMs and AMs, which helps observe their similarities and differences from the kinematic point of view.

The intervals of NM and AM can be technically determined in various ways. In the present method, the motion intervals were determined based on the average of each participant's 5th (lower limit) and 95th (upper limit) percentile ROMs. In contrast, the motion intervals can be defined using 5th (lower limit) and 95th (upper limit) percentile ROMs of all the participants, too. In this study, the former approach was employed to remove outliers in each participant's motion capture data and compute individual MS (%) between NM and AM for each participant.

Motion similarity (MS), a new usability index, was introduced to evaluate the physical usability of a product in the present study. We assumed that the kinematic motion similarity between NM and AM could be an effective criterion to measure users' satisfaction of product-use motion. Thus, MS (%) was computed based on the overlapped time-intervals between NM and AM which indicate simply how close AM is to NM. MS can demonstrate three utilities such as (1) a usability index, (2) a product design analysis tool, and (3) a kinematic analysis. First, quantified MS scores help recognize easily which product demonstrated a more similar motion to users' NM as well as rank immediately products by comparing their MS scores. Second, MS show the relationships and patterns with the physical design factors of products which may indicate that there are significant design directions to improve MS as well as useful supports to provide objective, user-preferred design changes. Lastly, MS quantitatively demonstrates that there are kinematic differences between NM and AM across the joints, motions, and products, which may be of use to improve the kinematic efficiency of product-use motion.

4.2 Case study

The existence of NM was identified through the usability test of the four vacuum cleaners (A, B, C, and D). The NM reliability analysis indicated that the participants have their own preferred cleaner-use motions. In the case study, the NMs showed high reliability within individual participant (average $SDme = 3.1^\circ$) but the biological variations (average $SDbv = 14.2^\circ$) between participants were relatively high. This high reliability of NM can be interpreted as that each participant has her own natural cleaner-use motion and the NM of each individual is different from those of others with a certain level of variation.

The vacuum cleaner case study demonstrated that the design specifications of the cleaners could not only determine cleaner-use motions but also limit NMs of users. The cleaner-use motions while holding the canisters might not work out the way the participants thought they would, since the participants showed clearly different AMs from their NMs from the kinematic point of view. In particular, while holding a canister, their shoulder swung the canister back and forth beside the body (-25.4° - 36.4°), which was a completely different swing motion from the participants' NMs whose shoulder swing occurred in front of the body (-4.6° - 56.6°). Also, the AMs had larger ROMs than the NMs across all the joint motions, which could be evidence that the shape, weight, or length of the canister might determine cleaner-use motions.

As a usability index, the quantified MS scores helped simply evaluate a physical usability of the cleaners in terms of the motion similarity between NM and AM. The average MS scores determined that, overall, the use motions of cleaners C and A were closer to the NMs than those of cleaners B and D. Also, the average MS rank enabled us to simply rank the cleaners in terms of the physical usability; e.g. cleaners C (average rank: 2.2) > A (2.4) > B (2.5) > D (2.9). In addition, we could investigate the variations of the MSs for joints at a glance; for example, the MS scores found that the cleaner-use motions at the shoulder, wrist, and lower back were relatively closer to the NMs than those of the other joints.

The case study found that there would be limitations of the participants' AMs to be improved while keeping the current canister use-mechanism. The relationship analysis between MSs and design specifications found that the current canister designs may cause a variety of design tradeoffs. For instance, when the canister length and weight declined (cleaners D to A), the MSs increased at the shoulder elevation/extension but the MSs of the neck flexion decreased simultaneously. Also, the lowest MS of the lower back left/right rotation was found at the canister with middle length and weight (e.g. cleaner C), while the lower back left/right lateral flexion had the highest MS on the same canister. These tradeoffs may not only make it difficult to optimize canister length and weight but also assign limits to the current canister design in providing better design solutions; in other words, as long as the current canister mechanism is maintained, any change of canister length and weigh cannot improve MSs of all the joint motions at the same time.

In the case study, the average EMG measurements were used to rank cleaners A, B, C, and D in terms of muscular efforts. In general, average EMG amplitudes have limitations in their reliability because they generally demonstrate large variations between individuals (Hansson et al., 2009; Nordander et al., 2004). However, the present study used average EMG because the case study focused ranking muscle activities of the four cleaners and ranks of average EMG were consistent between the participants.

The case study demonstrated that how MS is associated with muscle activities and subjective discomfort ratings. In the vacuum cleaner evaluation, the MSs had strong relationships with the EMG measurements but somewhat different patterns with subjective discomfort ratings. The ranks of the average EMG values among the four cleaners were well-matched with those in the MS scores, which could be interpreted as the product-use motions deviated from the NM may increase the muscular efforts. Meanwhile, the subjective discomfort ratings had different patterns from the MS results. In particular, cleaner A had higher discomfort ratings than cleaners B and C across all the discomfort ratings despite its better MS scores and EMG ranks. However, the difference was expected because subjective discomfort ratings are generally regarded as a comprehensive evaluation tool which might be affected by diverse factors aside from the kinetic and kinematic factors which were focused on the study. In the debriefing session of the case study, the participants were asked about the reasons, and they explained that the cleaning range of cleaner A was too small because it had a shorter canister than the other cleaners.

Through the vacuum cleaner evaluation, a new canister design, named a swiveling canister, can be practically proposed based on the design evaluations and directions by the proposed method. The novel swiveling canister design can provide several motion features which promote the use of NMs while cleaning. First, most of the arm swings during cleaning are completed in front of the body so that the shoulder extension is reduced. Second, excessive elbow flexion and wrist ulnar deviation can be prevented. Third, the lower back flexion can be reduced. Accordingly, a new arm swing mechanism can be developed as illustrated in Fig. 10: the handle swivels forward when the shoulder is extended and the handle swivels backward when the shoulder is elevated. Thus, the handle of the swiveling canister is capable of rotating in all directions with an elastic unit which elastically biases the handle to a neutral position (Lee et al., 2010).

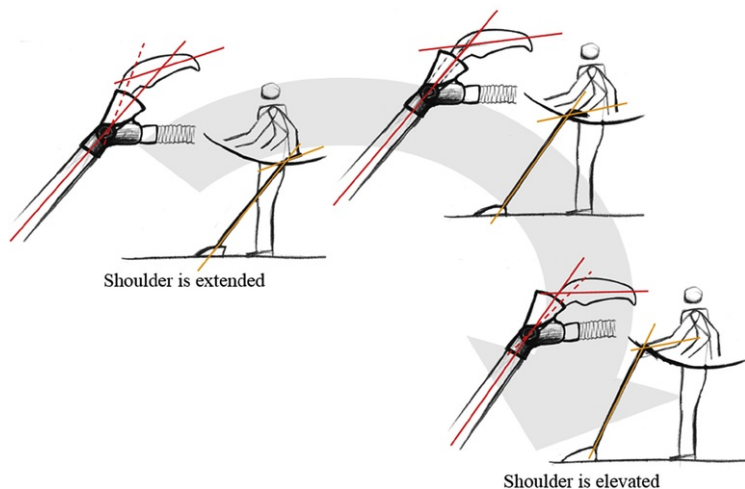


Fig. 10 Swiveling canister.

alt-text: Fig. 10

4.3 Limitations and future research

The experiment protocol of the present study needs to be improved in two aspects: (1) control of physical design elements of a product of interest and (2) experimental setup and task-design. First, each physical design factor

(e.g. length and weight) of the product should be controlled in the experiment. Since the case study used cleaners available from the market, each physical design element of cleaner could not be controlled in the experiment. For example, the length and weight of canisters were coupled together, resulting in difficulty to identify the effect of each individual physical design factor. Second, more elaborate experimental setup and task design are needed because they are likely to affect MS results. In the case study, the experimental protocol was controlled to effectively demonstrate the usefulness of the proposed usability evaluation method. However, some factors (e.g., foot location and direction of swiveling) which could significantly influence the MS were controlled rigorously in the experiment. Thus, a further study examining the effects of the experimental setup and task design is needed to minimize these effects on MS results.

The present study has several limitations in generalizing the proposed NM method. The proposed usability evaluation method was tested only in the application of vacuum cleaners. Although the present method showed the prospective results in the case study, its application should be extended to various products for generalization of its effectiveness and usefulness. Furthermore, users' preferred product-use motions can be comprehensive results influenced by a variety of factors including users' experience, age, gender, cognitive and behavioral patterns, and even anthropometric and biomechanical characteristics. For example, in the present study NMs were measured after a 10-min exercise, which was intended to help the participants not only be familiarized to use of the vacuum cleaners but also find their NMs. It would be meaningful to examine whether the NM of an individual is significantly changed by product experience. Thus, investigating the effects of the aforementioned factors on users' preferred product-use motions and understanding their mechanism can be useful for advancing the proposed method. Lastly, clustering analysis would be useful to identify a variety of representative NMs. In the present study, the biological variation of NMs varied largely, although a measurement error within each participant was small, which indicate that there would be representative groups sharing common features of NM among users.

5 Conclusion

The present study conceptually defined NM and proposed a new usability evaluation method under consideration of NM. The new proposed method introduced a quantitative measurement method of NM and AM using a motion capture system, and developed MS, a new usability index, which can examine the physical usability of a product based on the kinematic similarity between NM and AM. The method was tested for the validity with four vacuum cleaners (A, B, C, and D) with different designs. The case study demonstrated the usefulness as kinematic analysis and usability evaluation tools. This study has three expectations from the scientific and practical points of view. First, the defined NM could inspire product designers and engineers with a better understanding for the affordance of product-use, and motivate them to create new interaction designs between products and the users. Second, the proposed method may allow easy access to the systemically measurement of NM and AM on a target product and simple observation of the similarities and differences from the kinematic point of view. Lastly, as a usability tool, the quantified MS scores help usability engineers not only recognize easily which product produces a more similar product-use motion to users' NM, but also quickly rank products by comparing their MS scores.

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Highlights

- A new usability evaluation method was developed to examine products in terms of physical usability.
- The proposed method defined a new usability index based on the motion similarity (MS) between natural (NM) and actual product-use motions (AM).
- MS helped not only quantitatively recognize which product demonstrated a more similar motion to users' NM but also immediately rank products based on MS.
- The proposed method demonstrated that how MS is associated with muscle activities and subjective discomfort ratings in product-use.

Queries and Answers

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Answer: • The motion similarity (MS) between natural (NM) and actual product-use motions (AM) was proposed.

- MS quantitatively identified which product showed similar motions to users' NM and ranked products based on MS.
- MS was related to muscle activities and subjective discomfort ratings in product-use.

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