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Joint motion pattern classification by cluster analysis of kinematic, demographic, and subjective variables

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ABSTRACT

The purpose of this study is to identify joint motion patterns by classifying the full range of motion (ROM) into several sections. Forty participants were stratified by age and gender and they performed 18 full-swing motions at a self-selected speed. Joint angle, angular velocity, angular acceleration, and subjective discomfort rating were collected for each motion. *K*-means cluster analyses were used to classify joint motion patterns and ROM sections. The results showed that two or three clusters were mainly determined by the kinematic variables of angular velocity and acceleration. The motions of three clusters showed that the ROM sections of low and moderate velocity with moderate and high accelerations occurred in the initial (negative) and terminal (positive) phases, respectively, whereas those of high velocity with low acceleration were shown in the mid (neutral) phase. The motions of two clusters revealed that while the patterns of high velocity and high acceleration were found on the positive side of the ROM, those of low velocity and low acceleration were on the negative and neutral sides. The ROM sections close to both ends of the ROM may have a larger physical load than the others. This study provides information that could be useful for developing postural analysis tools for dynamic work.

1. Introduction

Work-related musculoskeletal disorders (WMSDs) show widespread inflammatory and degenerative symptoms that are commonly associated with the neck, shoulder, elbow, forearm, wrist, and hand (Buckle and Devereux, 2002). The main physical risk factors for WMSDs are a rapid work pace, repetitive motion, forceful manual exertion, awkward body posture, and vibration (Punnett and Wegman, 2004). In particular, awkward working postures at extreme joint angles can have a significant effect on a worker's musculoskeletal system (Armstrong et al., 1984). Various postural analysis tools have been developed to investigate the risk of WMSDs for the whole body (Karhu et al., 1977; Corlett et al., 1979; Armstrong et al., 1982; Keyserling, 1986; McAtamney and Corlett, 1993; Hignett and McAtamney, 2000). These methods are generally divided into pen-and-paper-based observational techniques and computer-aided observational methods involving videotaping (Li and Buckle, 1999).

Most postural analysis tools have a full range of motion (ROM) for each body segment divided into several sections. For instance, Armstrong et al. (1982) used sections of equivalent ranges for the upper extremity at intervals of 45°. Keyserling (1986) classified shoulder and trunk postures by considering angles of 20°, 45°, and 90°. He developed posture classifications from a previous study in which non-neutral postures had been associated with fatigue or musculoskeletal disorders. Rapid upper limb assessment (RULA) and rapid entire body assessment (REBA) categorized postures for the whole body using the positions 0°, 15°, 20°, 45°, 60°, 90°, and 100° (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000). They developed a method for recording postures based on the interpretation of relevant studies associated with each body segment. The shortcoming of the previous postural analysis tools is that several ROM sections are simply defined without rationale or developed by a simple combination of the results from previous studies. Thus, this non-rationale decision and inconsistent combination of results could loose the information of dynamic joint motions such as kinematic, kinetic, and physiological responses.

In addition, most studies on postural analysis tools have evaluated the physical workload, such as electromyographic (EMG) activity, for static postures. Herberts et al. (1980) investigated the localized muscle fatigue of the shoulder in eight static arm positions. They found that overhead work with 45° of abduction resulted in lower localized muscle fatigue than 0° or 90° of abduction. Hagberg (1981) also studied shoulder muscular fatigue at two different elevated arm positions. He reported that significant muscular fatigue occurred after 5 min at 90° of forward flexion and

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90° of abduction. Chaffin (1973) evaluated localized fatigue of the head and upper arm in different positions during continuous holding. He found a rapid increase in muscular fatigue at 30° of flexion for the head and 30° of abduction for the upper arm. However, there is a lack of reference data for dynamic motions. For example, Li et al. (2006) analyzed dynamic reaching behavior to Automatic Teller Machine for disabled people with wheelchair using a real-time virtual interactive design methodology. However, this study did not provide generalized ROM sections for postural analysis tools. In a dynamic situation, changes in force and muscle fiber length throughout the ROM significantly influence muscle activity (Larsson et al., 1999). Therefore, postural analysis tools based on static posture evaluation seem to be unsuitable for workplaces where dynamic motions are frequent.

Cluster analysis is often used to provide classifications, identify patterns of association, and divide samples into homogeneous groups for dynamic motions (Rapkin and Luke, 1993). This method is commonly used to classify motion or motion patterns in physical therapy, surgical communities, and ergonomics. Mulroy et al. (2003) performed gait pattern classification of patients with recovery phases based on kinematic parameters. Toro et al. (2007) extracted gait patterns in children with cerebral palsy using ROM variables for the hip, knee, and ankle. Rozumalski and Schwartz (2009) defined crouch gait patterns in patients with cerebral palsy based on age, ROM, strength, selective motor control, and spasticity. Kyung et al. (2010) also identified drivers' postural strategies for two vehicle types through the interpretation of several joint angles. In addition, Li and Zhang (2009) used the *K*-means cluster analysis to separate into two groups of lifting strategies based on the relative strength between the back and knees.

As mentioned earlier, most ROM sections of postural analysis tools evaluated the physical load of several predefined static postures. These static motion-based postural analysis tools have even been applied to dynamic working motions in an industrial field. Therefore, assessment of dynamic motions is necessary to develop more realistic postural analysis tools. The aim of this study is to evaluate the dynamic joint motions of the head, upper arm, lower arm, hand, trunk, upper leg, lower leg, and foot using cluster analysis of kinematic, demographic, and subjective variables in order to define ROM sections that have homogeneous motion characteristics.

2. Methods

2.1. Participants

Forty healthy participants (10 young males, 10 young females, 10 old males, and 10 old females) volunteered for the experiment. After informed consent, the participants were briefly provided with the details of the experimental purposes and procedures. They had no previous history of musculoskeletal disorders of the whole body. The average age, height, and body mass of the participants are reported in Table 1.

Table 1
Mean ± standard deviation of the participants' anthropometric dimensions.

Dimension	Young		Old		Mean
	Male	Female	Male	Female	
Age (years)	27.2 ± 1.2	23.4 ± 1.6	56.4 ± 3.2	56.9 ± 3.3	41.0 ± 15.9
Height (cm)	175.1 ± 4.3	160.5 ± 4.5	168.6 ± 3.9	155.9 ± 4.7	165.0 ± 8.6
Body mass (kg)	73.3 ± 10.7	54.5 ± 7.3	72.3 ± 9.2	58.1 ± 5.2	64.5 ± 11.8

2.2. Apparatus

In order to collect kinematic data of the joint motions, a motion capture system (VICON, Oxford, UK) was used with nine cameras at a sampling rate of 60 Hz. Twenty-two reflective surface markers with a diameter of 14 mm were adhered to the bony landmarks of the head, trunk, and right side of the upper arm, lower arm, hand, upper leg, lower leg, and foot based on the standard procedures of the Plug-In Gait model (VICON, Oxford, UK). VICON Nexus® software was used to process all the trials, and Polygon® software (VICON, Oxford, UK) was used to analyze the data.

2.3. Procedure

The anthropometric dimensions of the participants were measured with a caliper and a measuring tape. Surface markers were attached to the skin and body gymsuits worn by the participants. The right side of upper and lower extremity was measured and it was the dominant side for all subjects. For the initial posture, the participant stood and released his or her arms alongside the trunk with the palm facing the body. Each participant randomly tried 18 joint motions in the initial posture for the body segments without any restrictive straps. The joint motions of positive and negative directions were flexion-extension (F/E), right-left lateral flexion (R/L-LF), and right-left rotation (R/L-R) for the head; flexion-extension (F/E), abduction–adduction (AB/AD), and external–internal rotation (ER/IR) for the upper arm; flexion (F) for the lower arm; flexion-extension (F/E) and ulnar-radial deviation (UD/RD) for the hand; flexion-extension (F/E), right-left lateral flexion (R/L-LF), and right-left rotation (R/L-R) for the trunk; flexion-extension (F/E), abduction–adduction (AB/AD), and external–internal rotation (ER/IR) for the upper leg; flexion (F) for the lower leg; and plantar-dorsi flexion (PF/DF) and eversion-inversion (EV/IV) for the foot. In other words, flexion (F), right lateral flexion (R-LF), right rotation (R–R), abduction (AB), external rotation (ER), ulnar deviation (UD), plantar flexion (PF), and eversion (EV) had positive directions, while the other motions had negative directions based on a biomechanical coordinate system (Wu and Cavanagh, 1995). For the lower arm and lower leg, only 1 rotational angle was collected due to the physiological limitation such as hinge joints. The participants were encouraged to perform each joint motion as fully as possible by swinging the corresponding segment in order to reach the maximum ROM of both positive and negative directions at a self-selected speed. The participants continued repeating each joint motion for three cycles without pausing. For example, in one cycle the participant fully flexed, extended, and flexed the head again for the head F/E. For the lower extremity motions, the participant held an assistive frame to maintain balance. After each joint motion, the participant was provided with visual analog scales (VAS) and rated the overall levels of comfort and discomfort. The subjective ratings were measured numerically: 0 indicated very comfortable and 100 indicated very uncomfortable.

2.4. Data analysis

A Woltring filter with a mean-square error value of 20 was implemented to filter the raw marker trajectories, and then ROM, angular velocity and angular acceleration were obtained. The time-normalization (0–100%) of ROM, angular velocity and angular acceleration was performed to calculate and compare between six different motions for each joint motion with Polygon® software. The initial and final time point was the minimum and maximum range of motion for each joint motion. For example, three flexion and three extensions were actually performed during three cycles of head F/E, and then time-normalization was conducted for each motion, respectively. Based on the normalized time, the ensemble kinematic pattern such as ROM, angular velocity, and angular acceleration were obtained based on the three flexion and three extensions of head F/E. The average motion pattern of head F/E including ROM, angular velocity and angular acceleration by whole participants is shown in Fig. 1. This whole procedure was applied to the rest of other joint motions.

For the ROM, angular velocity and angular acceleration, extreme outliers were removed out of mean $\pm$ (2.58 $\times$ standard deviation). The full data set of ROM, angular velocity and angular acceleration for each joint motion was 4040 (40 participants $\times$ 101 normalized time points from 0% to 100%), respectively. However, actual datasets varied from 3535 to 4040 due to the outlier removal of ROM, angular velocity and angular acceleration. The actual datasets for each joint motion was determined based on the minimum datasets from ROM, angular velocity and angular acceleration. As a result, hand F/E had 3535 data set; upper arm ER/IR, trunk R/L-LF, lower leg F and foot EV/IV had 3737 data set; hand UD/RD and upper leg F/E had 3838 data set; head R/L-LF and R/L-R, lower arm F, trunk F/E and R/L-R, upper leg AB/AD and foot PF/DF had 3939 datasets; head F/E, upper arm F/E and AB/AD and upper leg ER/IR had 4040 datasets. Subjective ratings for each participant were also normalized by equation (1) to reduce response bias between participants.

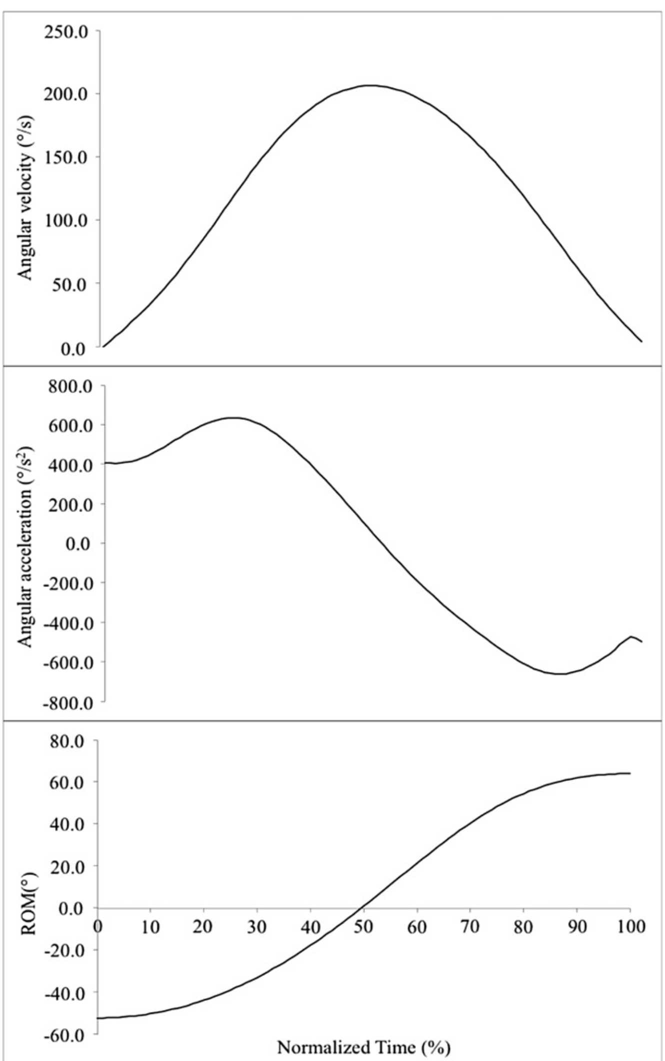

Fig. 1. The example of average motion pattern for head F/E.

$$N = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \times 100 \tag{1}$$

where N denotes normalized subjective ratings, x_i denotes the subjective rating of each joint motion, $x_{\min}$ is the minimum subjective rating of 18 joint motions, and $x_{\max}$ is the maximum subjective rating of 18 joint motions.

The nonhierarchical K-means clustering objective function was used to define clusters that showed different characteristics of ROM sections in each joint motion. The random initial centroid was selected, and then iteration and reassigning elements were performed until they find the minimum distance to centroid. This method is faster than hierarchical clustering methods and minimizes variance within clusters (Carayon, 1994). The kinematic variables were used as the ensemble of angular velocity and angular acceleration. Those measures included the average motion pattern of each repetitive joint motion for each subject, and they were highly related to the dynamic motion (Sjölander et al., 2008). The demographic variables were age and gender, and subjective variable was the subjective ratings of comfort and discomfort since they were significant factors that affected ROM (Genaidy and Karwowski, 1993; Doriot and Wang, 2006). Thus, input variables for cluster analysis were determined as angular velocity, angular acceleration, age, gender and subjective ratings. If the joint motion does not have outliers, 4040 datasets of each variable were analyzed. The ROM was determined as the composition of final clusters. The Z-score standardization of variables was conducted using mean and standard deviations of each variable in order to balance the effect of different units (equation (2)).

$$Z - \text{score} = \frac{\text{mean(cluster)} - \text{mean(total)}}{\text{SD(total)}} \tag{2}$$

The initial $k = 2$, 3, 4, 5 and 6 were empirically conducted and compared to find the optimal number of clusters for each joint motion. The optimal number of final clusters for each joint motion was determined based on the following criteria: First, the interpretation of clusters should not be complicated, and it was decided based on a visual examination of mean and proportion data for all variables (Everitt et al., 2001); Second, the optimal number of clusters was also determined by the data points of each cluster. If the data points of one or two clusters were too small ($<$50) or too large ($>$3700), the clusters were formed again because small data points could increase the within group variability, and large data points could decrease the difference between clusters (Mulroy et al., 2003); Third, resulting ROM sections associated clusters for each joint motion should be distinguishable among divided clusters. Thus, the one-way repeated analyses of variance (ANOVA) with a significance level of 0.05 were performed for each joint motion to analyze the statistical difference of ROM sections across clusters. Independent variable was the type of cluster ($n = 2$ or 3) and dependent variable was the ROM associated with clusters. ANOVA was repeatedly conducted for each joint motion. SAS statistical software (version 9.1) was used to conduct the analyses (SAS, Cary, USA).

3. Results

Table 2 shows the results of cluster analysis and mean and standard deviation of angular velocity, angular acceleration, and subjective ratings for each joint motion. Two or three clusters for each joint motion were identified based on the criteria mentioned

Table 2
Cluster analysis results and mean ± standard deviation of angular velocity, angular acceleration, and subjective rating. The letters L, M, H, V, and A indicate low, moderate, high, velocity, and acceleration, respectively, in the cluster column. The motions with two clusters have only LV-LA and HV-HA, whereas those with three clusters have only LV-MA, HV-LA, MV-MA, and MV-HA.

Segment	Motion	Cluster	No. of data	Angular velocity (°/s)	Angular acceleration (°/s^2)	Subjective rating (%)
Head	F/E	1 (LV-LA)	3034	109.9 ± 77.2	207.2 ± 457.1	45 ± 32
		2 (HV-HA)	1006	136.3 ± 76.2	−614.1 ± 445.5	24 ± 25
	R/L-LF	1 (LV-MA)	1739	39.7 ± 39.0	196.9 ± 303.6	57 ± 36
		2 (HV-LA)	1365	121.4 ± 50.1	113.2 ± 332.6	32 ± 34
		3 (MV-HA)	835	87.0 ± 48.0	−599.2 ± 279.5	60 ± 33
	R/L-R	1 (LV-LA)	3528	153.5 ± 124.5	221.7 ± 885.6	31 ± 29
		2 (HV-HA)	411	248.7 ± 124.0	−1910.4 ± 1106.4	40 ± 30
Upper arm	F/E	1 (MV-MA)	1839	146.4 ± 93.8	531.0 ± 443.5	16 ± 16
		2 (HV-LA)	1285	253.0 ± 83.8	−29.1 ± 644.8	51 ± 32
		3 (LV-HA)	916	132.9 ± 81.9	−974.5 ± 562.0	21 ± 20
	AB/AD	1 (LV-LA)	2164	161.9 ± 87.4	510.0 ± 399.6	34 ± 31
		2 (HV-HA)	1876	167.0 ± 86.1	−572.1 ± 436.5	38 ± 32
	ER/IR	1 (LV-LA)	2045	121.8 ± 116.0	625.4 ± 1238.1	20 ± 23
		2 (HV-HA)	1692	263.8 ± 141.6	−737.9±1184.8	43 ± 34
Lower arm	F	1 (HV-HA)	1823	164.9 ± 118.8	672.6 ± 769.7	10 ± 14
		2 (LV-LA)	2116	156.3 ± 109.4	−602.8 ± 1022.2	2 ± 5
Hand	F/E	1 (LV-LA)	1950	142.9 ± 106.9	1053.7 ± 967.4	27 ± 29
		2 (HV-HA)	1585	184.6 ± 112.0	−1260.7 ± 1129.0	27 ± 26
	UD/RD	1 (LV-LA)	2773	93.2 ± 78.8	452.5 ± 714.8	53 ± 34
		2 (HV-HA)	1065	131.2 ± 95.2	−1189.9 ± 739.8	53 ± 36
Trunk	F/E	1 (MV-MA)	1613	36.9 ± 23.9	95.9 ± 101.1	80 ± 23
		2 (HV-LA)	1164	63.2 ± 28.1	12.8 ±121.2	40 ± 30
		3 (LV-HA)	1162	32.4 ± 22.6	−140.5 ± 107.3	72 ± 26
	R/L-LF	1 (MV-MA)	1265	32.5 ±17.9	139.5 ±125.4	64 ± 30
		2 (HV-LA)	1445	71.5 ± 16.4	−1.4 ± 100.0	39 ± 26
		3 (LV-HA)	1027	31.4 ±17.4	−174.5 ± 126.4	51 ± 27
	R/L-R	1 (LV-MA)	1956	32.4 ± 20.7	131.6 ± 115.0	57 ± 33
		2 (HV-LA)	882	95.5 ± 25.2	60.5 ± 195.5	43 ± 33
		3 (MV-HA)	1101	41.5 ± 25.9	−282.6 ± 180.0	59 ± 35
Upper leg	F/E	1 (MV-MA)	1543	88.4 ± 52.4	514.1 ± 392.8	58 ± 31
		2 (HV-LA)	1643	188.2 ± 58.6	−131.0 ± 574.3	39 ± 32
		3 (LV-HA)	652	67.4 ± 48.8	−852.5 ± 529.3	65 ± 31
	AB/AD	1 (LV-LA)	2324	66.3 ± 48.7	125.5 ± 436.9	31 ± 31
		2 (HV-HA)	1615	119.1 ± 58.2	−177.2 ± 545.6	70 ± 30
	ER/IR	1 (HV-HA)	1648	60.5 ± 44.7	274.8 ± 432.5	66 ± 34
		2 (LV-LA)	2392	40.4 ± 33.0	−184.8 ± 396.3	46 ± 33
Lower leg	F	1 (LV-LA)	2670	161.5 ± 105.5	705.4 ± 1015.9	30 ± 31
		2 (HV-HA)	1067	260.3 ± 129.4	−1689.2 ± 1547.5	38 ± 37
Foot	PF/DF	1 (HV-HA)	1300	137.9 ± 103.0	1232.4 ± 808.6	35 ± 33
		2 (LV-LA)	2639	107.6 ± 90.6	−600.1 ± 629.2	31 ± 31
	EV/IV	1 (HV-HA)	54	113.8 ± 106.1	2505.2 ± 1718.7	96 ± 8
		2 (LV-LA)	3683	33.0 ± 31.1	−44.3 ± 498.4	61 ± 35

in the data analysis. In general, the final clusters had distinct characteristics without any difficulty of interpretation. According to the weight scores that explained the proportion of the data representing the clusters, the kinematic variables of angular velocity and angular acceleration best characterized the clusters of joint motions (ranging from 0.7 to 1), whereas the subjective variable of comfort and discomfort rating was less important except for F/E of the head, F/E of the upper arm, F of the lower arm, and F/E and R/L-LF of the trunk. The demographic variables of age and gender were also less important except for F of the lower arm and AB/AD and ER/IR of the upper leg.

Each motion had either two or three clusters. The low, moderate, and high levels of angular velocity and acceleration were categorized for each joint motion based on the absolute values-comparison among clusters. The motions of F/E and R/L-R of the head, AB/AD and ER/IR of the upper arm, F of the lower arm, F/E and UD/RD of the hand, AB/AD and ER/IR of the upper leg, F of the lower leg, and PF/DF and EV/IV of the foot were classified into two clusters that had the motion patterns of either "low velocity and low acceleration (LV-LA)" or "high velocity and high acceleration (HV-HA)" according to the absolute magnitudes of angular velocity and angular acceleration. However, the other six motions of R/L-LF of the head, F/E of the upper arm, F/E, R/L-LF, and R/L-R of the trunk, and F/E of the upper leg were classified into three clusters that had the motion patterns of either "low velocity and moderate acceleration (LV-MA)," "moderate velocity and high acceleration (MV-HA)," "moderate velocity and moderate acceleration (MV-MA)," or "high velocity and low acceleration (HV-LA)."

Generally, the participants revealed larger discomfort at moderate or high accelerations than at low acceleration regardless of the magnitude of the angular velocities. For example, the subjective ratings were 96% in cluster 1 (HV-HA) for EV/IV of the foot and 80% and 72% in clusters 1 (MV-MA) and 3 (LV-HA) for F/E of the trunk, respectively.

Table 3 displays the proportion of demographic variables for each joint motion. Since demographic variables were categorical (nominal) data, cross-tab analysis was conducted to assess the distribution of age and gender within each cluster for joint motions (Table 3). In overall, most joint motions showed that there was no consistent pattern for age and gender distribution between clusters. It indicated that age and gender were generally not primary variables in developing clusters for each joint motion.

The ANOVA results indicate that the ROM sections were significantly different between clusters for each joint motion ($p < 0.0001$). Fig. 2 displays the sections of the full ROM for each joint motion. Among the joint motions with three clusters, cluster 1

Table 3
Proportion of demographic variables for each joint motion. The motions with two clusters have only LV-LA and HV-HA, whereas those with three clusters have LV-MA, HV-LA, MV-MA, and MV-HA.

Segment	Motion	Demographic variable	Cluster 1 (%)		Cluster 2 (%)		Cluster 3 (%)	
Head	F/E	Young vs. Old	56.5	43.5	31.0	69.0	–	
		Male vs. Female	56.7	43.3	31.4	68.6	–	
	R/L-LF	Young vs. Old	51.2	48.8	46.8	53.2	47.7	52.3
		Male vs. Female	65.5	34.6	21.6	78.4	66.1	33.9
	R/L-R	Young vs. Old	55.3	44.7	19.3	80.7	–	
		Male vs. Female	46.5	53.5	62.8	37.2	–	
Upper arm	F/E	Young vs. Old	43.5	56.5	50.8	49.2	62.6	37.4
		Male vs. Female	38.2	61.8	76.6	23.4	35.5	64.5
	AB/AD	Young vs. Old	48.7	51.3	51.8	48.2	–	
		Male vs. Female	47.6	52.4	52.5	47.5	–	
	ER/IR	Young vs. Old	33.0	67.0	73.2	26.8	–	
		Male vs. Female	51.8	48.3	43.4	56.6	–	
Lower arm	F	Young vs. Old	46.1	53.9	51.5	48.6	–	
		Male vs. Female	25.5	74.5	72.7	27.3	–	
Hand	F/E	Young vs. Old	48.9	51.2	42.3	57.7	–	
		Male vs. Female	57.2	42.8	67.2	32.8	–	
	UD/RD	Young vs. Old	54.3	45.7	32.0	68.0	–	
		Male vs. Female	54.7	45.3	43.4	56.6	–	
Trunk	F/E	Young vs. Old	72.4	27.6	22.5	77.5	50.3	49.7
		Male vs. Female	61.7	38.3	40.4	59.6	37.4	62.6
	R/L-LF	Young vs. Old	29.2	70.8	60.7	39.3	65.7	34.4
		Male vs. Female	56.1	43.9	40.8	59.2	56.8	43.2
	R/L-R	Young vs. Old	49.5	50.5	60.8	39.3	38.8	61.2
		Male vs. Female	47.2	52.8	53.2	46.8	45.2	54.8
Upper leg	F/E	Young vs. Old	51.2	48.9	49.3	50.8	50.7	49.3
		Male vs. Female	62.3	37.7	39.1	60.9	45.1	54.9
	AB/AD	Young vs. Old	48.1	51.9	50.2	49.8	–	
		Male vs. Female	26.9	73.1	85.0	15.0	–	
	ER/IR	Young vs. Old	11.3	88.7	76.3	23.7	–	
		Male vs. Female	56.4	43.6	45.5	54.5	–	
Lower leg	F	Young vs. Old	59.0	41.0	42.0	58.0	–	
		Male vs. Female	61.1	38.9	37.1	62.9	–	
Foot	PF/DF	Young vs. Old	48.5	51.5	52.7	47.3	–	
		Male vs. Female	52.5	47.5	50.6	49.4	–	
	EV/IV	Young vs. Old	80.7	19.4	48.5	51.6	–	
		Male vs. Female	80.7	19.4	55.2	44.9	–	

(LV-MA) or (MV-MA) were generally related with the negative ROM sections of extension (E), left lateral flexion (L-LF), and left rotation (L-R), whereas cluster 3 (MV-HA) or (LV-HA) were related to the positive ROM sections of flexion (F), right lateral flexion (R-LF), and right rotation (R–R). Cluster 2 (HV-LA) was generally associated with the middle ROM sections around neutral positions of the body segments between negative and positive sections. For the joint motions with two clusters, cluster 1 (LV-LA) was related to negative and neutral ROM sections of extension (E), left rotation (L-R), adduction (AD), internal rotation (IR), radial deviation (RD), dorsiflexion (DF), and inversion (IV), while cluster 2 (HV-HA) was associated with the positive ROM sections of the opposite sides of the motions.

4. Discussion

The purpose of the present study is to identify joint motion patterns and to use cluster analysis to provide the sections of the ROM that have similar kinematic, demographic, and subjective characteristics for each joint motion. The joint motions had either two or three clusters on the basis of the cluster selection criteria established in the data analysis.

The R/L-LF of the head, F/E of the upper arm, F/E, R/L-LF, and R/L-R of the trunk, and F/E of the upper leg belonged to three cluster groups. These joint motions had the initial phase with low velocity and moderate acceleration in cluster 1 and the terminal phase with low velocity and high acceleration in cluster 3. These phases of clusters 1 and 3 might be associated with considerable muscle forces because angular acceleration had a positive correlation with forces due to the Newtonian laws of physics (Marras and Wongsam, 1986). The large contractions in agonist muscles would generate an acceleration of the body segments during the initial phase of motion, while the large co-contractions of agonist and antagonist muscles would cause a deceleration during the terminal phase of motion (Hagood et al., 1990). The motion pattern of high velocity and low acceleration was found in the midphase of motion in cluster 2 because both the decreased contraction in agonist muscles and the increased contraction in antagonist muscles could maintain the fast but rather constant angular velocity of the segments with low acceleration (Hagood et al., 1990). Thus, it can be said that muscles require large contractions to start and stop motions with moderate and high accelerations at both ends of the ROM, as shown in Fig. 1. However, muscles with relatively small contractions are necessary in the middle ROM sections (cluster 2), which have fast but smooth motion patterns around the neutral positions of the segments.

F/E and R/L-R of the head, AB/AD and ER/IR of the upper arm, F of the lower arm, F/E and UD/RD of the hand, AB/AD and ER/IR of the upper leg, F of the lower leg, and PF/DF and EV/IV of the foot had the classifications of two clusters. Most clusters of high velocity and high acceleration generally belonged to the positive ROM sections of flexion (F), right rotation (R–R), abduction (AB), external rotation (ER), and ulnar deviation (UD), whereas the clusters of low velocity and low acceleration were revealed in the negative and middle (or neutral) ROM sections. The bone structure and connective tissue at the joints can restrict the motions in the negative ROM sections, which have relatively narrower ROM than that in the positive sections. For example, the head, which can flex up to 64°, has

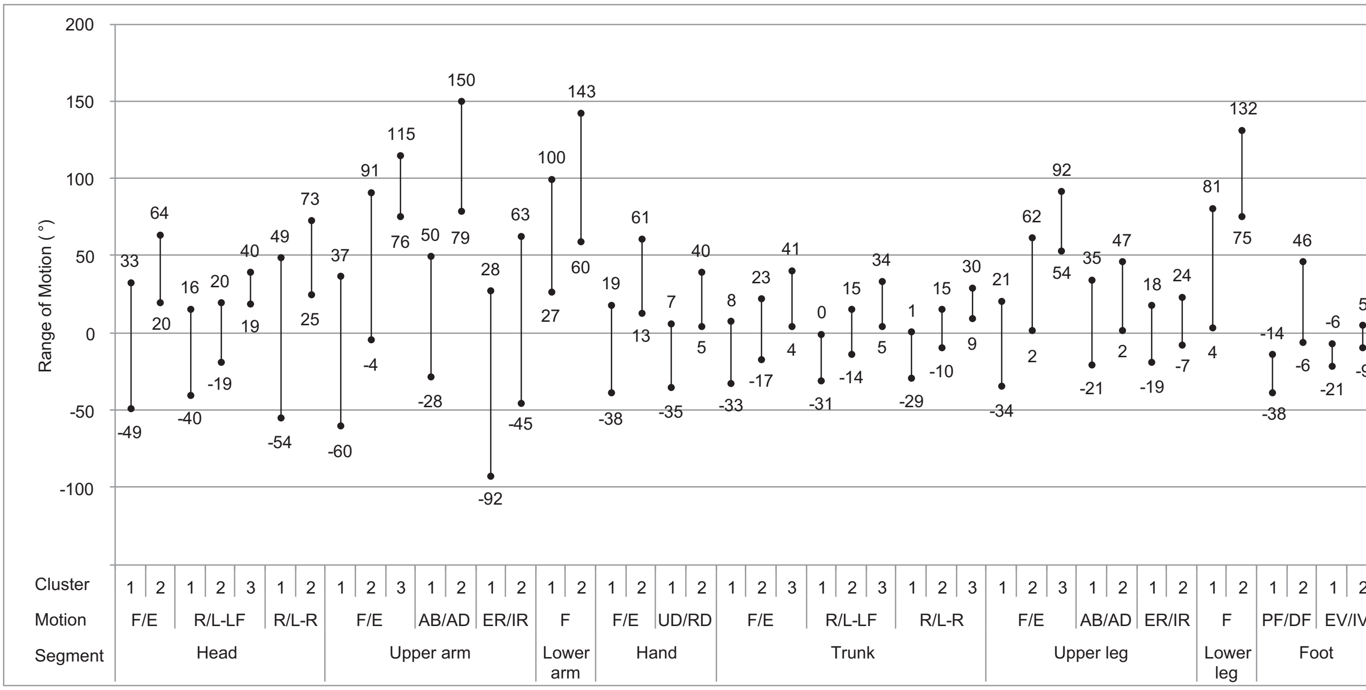

Fig. 2. ROM sections by cluster analysis for joint motions. The vertical bars represent ROM sections obtained from mean joint angle ± standard deviation in each cluster.

enough ROM to accelerate it in the positive section, but it can extend only up to −49°, which may not be sufficient for its acceleration. As mentioned earlier, however, the body segments seemed to require more muscle contractions in the positive ROM sections due to high acceleration than those in the negative and neutral sections. This agrees with the findings of Armstrong et al. (1984) that postures at extreme angles significantly influence physical stress.

The subjective discomfort ratings accounted for only F/E of the trunk and EV/IV of the foot. Unlike the other body segments, the trunk is a body segment that may be large enough for participants to feel discomfort even in a simple swaying motion because of its mass. However, the reason that the participants feel discomfort in the eversion and inversion of the foot may be due to the fact that those are rather difficult motions to perform continuously in a narrow ROM. Both trunk and foot motions also had large subjective ratings in the clusters of moderate and high accelerations, which might require large muscular effort and thus cause discomfort.

Similar to the subjective ratings, the demographic variables, age and gender, showed no apparent and consistent effects on the motion patterns including angular velocity and angular acceleration (Table 3). Such swaying motions without any external load may be too simple for the participants to perform, so that they feel rather comfortable with those motions. Thus, the confounding effect of age and gender on kinematics variables was considered to be less significant.

The results showed that several particular joint motions had considerable outliers due to the misunderstanding of instructions and unsmooth motions by old participants. For example, hand F/E had the lowest datasets as 3535 because five participants failed to follow the right instructions such as comfortable and consistent self-selected speed during the joint motion. In addition, upper arm ER/IR, trunk R/L-LF, lower leg F and foot EV/IV showed 3737 datasets. It was found that several old participants performed unsmooth motions for particular joint motions, so this lead to the outliers of angular acceleration.

The results of this study could provide new types of dynamic ROM sections compared to the other existing methods. For motions with two clusters, the overlapped region was selected as the neutral ROM ranges regarding the typical motion pattern. For motions with three clusters, cluster 2 regions were selected as the neutral ROM ranges. The neutral ROM ranges for each joint motion was head F/E (20° ~ 33°), RL-LT (−19° ~ 20°), and R/L-R (25° ~ 49°); upper arm F/E (−4° ~ 91°), AB/AD (50° ~ 79°), and ER/IR (−45° ~ 28°); lower arm F (60° ~ 100°); hand F/E (13° ~ 19°) and UD/RD (5° ~ 7°); trunk F/E (−17° ~ 23°), R/L-LF (−14° ~ 15°), and R/L-R (−10° ~ 15°); upper leg F/E (2° ~ 62°), AB/AD (2° ~ 35°), and ER/IR (−7° ~ 18°); lower leg F (75° ~ 81°); foot PF/DF (−14° ~ −6°) and EV/IV (−9° ~ −6°). Those neutral ROM ranges tended to have more positive deviations than the existing methods. For example, RULA and REBA showed the −15° ~ 15° deviation for neutral section for wrist F/E, whereas our result showed 13° ~ 19°. For head F/E, REBA showed 0° ~ 20° while our results showed 20° ~ 33°. This might be due to the different characteristics of motion such as angular velocity and acceleration and physiological response such as muscle length-changes compared to the static postures.

5. Conclusion

Cluster analysis is used to determine ROM sections for 18 motions of 8 segments that have similar joint motion patterns. The joint motions are mainly characterized by the kinematic variables angular velocity and angular acceleration, unlike the subjective variables comfort and discomfort and the demographic variables age and gender. The sections around both ends of the ROM show moderate and high accelerations due to muscle contractions, whereas the sections around a neutral range in the ROM display fast and smooth motion with low acceleration. This study quantitatively showed the difference of ROM sections between dynamic motions and static postures in terms of developing the postural analysis tools. This finding could be useful to design dynamic work tasks and develop advanced dynamics postural analysis tools for the future study.

The limitations of this study include the exclusion of physiological assessments such as muscle activities to identify the physical load for each ROM section. Moreover, the participants performed simple swing motions at their own speeds because self-selected speeds might be more appropriate to evaluate their functional capability in daily life (Mcgregor et al., 1997). However, these motions do not fully represent the motions in daily and workplace activities, so it should be cautious to apply the findings in tasks that involve restricted range of motion, longer duration and controlled speed. In addition, since anatomical variability could affect the motion and force patterns, a probabilistic biodynamic model would be recommended in the future to control inter-person and motion-dependent variability (Li and Zhang, 2010).

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References

Armstrong, T.J., Castelli, W.A., Evans, F.G., Diaz-Perez, R., 1984. Some histological changes in carpal tunnel contents and their biomechanical implications. J. Occup. Med. 26, 197–201.

Armstrong, T.J., Foulke, J.A., Joseph, B.S., Goldstein, S.A., 1982. Investigation of cumulative trauma disorders in a poultry processing plant. Am. Ind. Hyg. Assoc. J. 43, 103–116.

Buckle, P.W., Devereux, J.J., 2002. The nature of work-related neck and upper limb musculoskeletal disorders. Appl. Ergon. 33, 207–217.

Carayon, P., 1994. Stressful jobs and non-stressful jobs: a cluster analysis of office jobs. Ergonomics 37, 311–323.

Chaffin, D.B., 1973. Localized muscle fatigue—definition and measurement. J. Occup. Med. 15, 346–354.

Corlett, E.N., Madeley, S.J., Manenica, I., 1979. Posture targeting: a technique for recording working postures. Ergonomics 22, 357–366.

Doriot, N., Wang, X., 2006. Effects of age and gender on maximum voluntary range of motion of the upper body joints. Ergonomics 49, 269–281.

Everitt, B., Landau, S., Leese, M., 2001. Cluster Analysis. Edward Arnold, London.

Genaidy, A.M., Karwowski, W., 1993. The effects of neutral posture deviations on perceived joint discomfort ratings in sitting and standing postures. Ergonomics 36, 785–792.

Hagberg, M., 1981. Electromyographic signs of shoulder muscular fatigue in two elevated arm positions. Am. J. Phys. Med. 60, 111–121.

Hagood, S., Solomonow, M., Baratta, R., Zhou, B.H., D'ambrosia, R., 1990. The effect of joint velocity on the contribution of the antagonist musculature to knee stiffness and laxity. Am. J. Sports Med. 18, 182–187.

Herberts, P., Kadefors, R., Broman, H., 1980. Arm positioning in manual tasks: an electromyographic study of localized muscle fatigue. Ergonomics 23, 655–665.

Hignett, S., McAtamney, L., 2000. Rapid entire body assessment (REBA). Appl. Ergon. 31, 201–205.

Karhu, O., Kansi, P., Kuorinka, I., 1977. Correcting working postures in industry: a practical method for analysis. Appl. Ergon. 8, 199–201.

Keyserling, W.M., 1986. A computer-aided system to evaluate postural stress in the workplace. Am. Ind. Hyg. Assoc. J. 47, 641–649.

Kyung, G., Nussbaum, M.A., Babski-Reeves, K.L., 2010. Enhancing digital driver models: identification of distinct postural strategies used by drivers. Ergonomics 53, 375–384.

Larsson, B., Mansson, B., Karlberg, C., Syvertsson, P., Elert, J., Gerdle, B., 1999. Reproducibility of surface emg variables and peak torque during three sets of ten dynamic contractions. J. Electromyogr. Kinesiol. 9, 351–357.

Li, G., Buckle, P., 1999. Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics 42, 674–695.

Li, K., Duffy, V.G., Zheng, L., 2006. Universal accessibility assessments through virtual interactive design. Int. J. Hum. Factor. Model. Simulation 1, 52–68.

Li, K., Zhang, X., 2009. Can relative strength between the back and knees differentiate lifting strategy? Hum. Factor. 51, 785–796.

Li, K., Zhang, X., 2010. A probabilistic finger biodynamic model better depicts the roles of the flexors during unloaded flexion. J. Biomech. 43, 2618–2624.

Marras, W.S., Wongsam, P.E., 1986. Flexibility and velocity of the normal and impaired lumbar spine. Arch. Phys. Med. Rehabil. 67, 213–217.

McAtamney, L., Corlett, E.N., 1993. Rula: a survey method for the investigation of work-related upper limb disorders. Appl. Ergon. 24, 91–99.

Mcgregor, A.H., Mccarthy, I.D., Dore, C.J., Hughes, S.P., 1997. Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies of this motion. Eur. Spine J. 6, 308–315.

Mulroy, S., Gronley, J., Weiss, W., Newsam, C., Perry, J., 2003. Use of cluster analysis for gait pattern classification of patients in the early and late recovery phases following stroke. Gait Posture 18, 114–125.

Punnett, L., Wegman, D.H., 2004. Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. J. Electromyogr. Kinesiol. 14, 13–23.

Rapkin, B.D., Luke, D.A., 1993. Cluster analysis in community research: epistemology and practice. Am. J. Community Psychol. 21, 247–277.

Rozumalski, A., Schwartz, M.H., 2009. Crouch gait patterns defined using k-means cluster analysis are related to underlying clinical pathology. Gait Posture 30, 155–160.

Sjölander, P., Michaelson, P., Jaric, S., Djupsjöbacka, M., 2008. Sensorimotor disturbances in chronic neck pain—range of motion, peak velocity, smoothness of movement, and repositioning acuity. Man. Ther. 13, 122–131.

Toro, B., Nester, C.J., Farren, P.C., 2007. Cluster analysis for the extraction of sagittal gait patterns in children with cerebral palsy. Gait Posture 25, 157–165.

Wu, G., Cavanagh, P.R., 1995. ISB recommendations for standardization in the reporting of kinematic data. J. Biomech. 28, 1257–1261.