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ARTICLE

Prediction model of the effect of postural interactions on muscular activity and perceived exertion

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ABSTRACT
Musculoskeletal disorders are a prevalent disease in many Western countries. While a large number of ergonomic analyses and assessment methods are nowadays available, most current methods that assess exposure calculate overall risk scores of individual body segments without considering interaction effects of exposure variables. Therefore, a study was conducted that aimed at investigating and quantifying interaction effects of trunk inclination and arm lifting on ratings of perceived exertion (RPE) and muscle activity. A multiple regression model to predict musculoskeletal load under consideration of interaction effects was derived. The study revealed that there is a significant interaction effect of trunk inclination and arm lifting. Furthermore, final regression models explained variance in exposure variables in a range of $R^2 = 0.68$ to $R^2 = 0.147$ with a subset of two to three inputs. The predicative equations support the computer-based post-processing of sensor data.

Practitioner summary: This article elaborates on the importance of interaction effects of working postures on assessment results of load. In practise, easy to-use-methods for an assessment of working postures are needed. Therefore, a regression model is derived, which facilitates the quantification of work load under consideration of interaction effects. The use of this regression model for the assessment of posture data gathered by range sensors is recommended.

Abbreviations: RPE: rating of perceived exertion; MSD: musculoskeletal disorder; OWAS: ovako working posture analysing system; RULA: rapid upper limb assessment; LUBA: postural loading on the upper body assessment; REBA: rapid entire body assessment; OCRA: occupational repetitive action;S D: standard deviation; EMG: surface electromyography; LUT: left upper trapezius pars descendens; RUT: right upper trapezius pars descendens; LLT: left trapezius pars ascendens; RLT: right trapezius pars ascendens; LAD: left anterior deltoideus; RAD: right anterior deltoideus; LES: left erector spinae longissimus; RES: right erector spinae longissimus; SENIAM: surface electroMyoGraphy for the non-invasive assessment of muscles; MVC: maximum voluntary contraction; MANOVA: multivariate analysis of variance; ANOVA: analysis of variance; OLS: ordinary least squares; MANCOVA: multivariate analysis of covariance

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Postural load; working postures; workplace design; multiple regression

1. Introduction

Musculoskeletal disorders (MSDs) are prevalent worldwide and are associated with significant financial and social expenses. To identify hazardous working conditions, a wide range of ergonomic analyses and assessment methods have been developed. An overview of these methods regarding reliability and validity is provided by Denis, Lortie, and Rossignol (2000), David (2005) and Takala et al. (2010). Most of these methods were developed to consider individual aspects of work situations and for use as simple pen and paper methods. For example, OWAS (Karhu, Kansi, and Kuorinka 1977), which allows a whole body analysis and assessment, reduces complexity by a rough subdivision of the body segments. Further examples are RULA (McAtamney and Corlett 1993), which is limited to analysing and assessing working postures of the upper limbs and LUBA (Kee and Karwowski 2001b). Moreover, REBA (Hignett and McAtamney 2000) is a method which was developed to assess typical working postures in the field of health care (Hignett and

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McAtamney 2000). REBA is a method which allows practitioners to assess the overall musculoskeletal risk exposure based on angles from several body segments.

Overall, such methods can be utilised quickly and allow for a general assessment of working conditions; however, they are limited in their precision due to the disregard of interaction effects of exposure variables, e.g. working postures (EN 1005-4 2009; Lim, Jung, and Kong 2011).

Interaction effects are an interplay of several individual effects which can lead to an additional increase in musculoskeletal exposure. Interaction effects can result from a combination of body segment postures. The individual body segment postures may be characterised by a low exposure level. However, the resulting interaction effects of combinations of such body segment postures may lead to a hazardous level of exposure (Lim, Jung, and Kong 2011; EN 1005-4 2009). For example, musculoskeletal exposure during lifting tasks is influenced by the inclination of the trunk. Besides the trunk inclination, the inclination of the shoulder influences the musculoskeletal exposure during lifting tasks as well. This influence arises from different shoulder angles, which determines the lever arm of the load and subsequent the torque resulting in the spine. Therefore, musculoskeletal exposure during lifting tasks is dependent on two factors and their interaction. Moreover, exposure is determined by further exposure factors, for instance, elbow posture or wrist posture. According to EN 1005-4 angels of static arm lifting between 20° and 60° degree are only acceptable for short time durations or if there is full arm support. Furthermore, EN 1005-4 evaluates angles of static arm lifting above 60° as not acceptable for long durations. Angles of back inclination up to 20° are evaluated as conditionally acceptable and back inclination angles above 60° are evaluated at not acceptable by EN 1005-4.

Regarding the different methods, David (2005) investigated the epidemiological data upon the following methods were built: OWAS, RULA, OCRA, REBA, LUBA, NIOSH Lifting Equation etc., which revealed a limitation to the quantification of interaction effects. Besides these findings of David (2005), research findings have shown relevance of interaction effects between postures of shoulder, elbow, wrist and trunk. O'Sullivan and Gallwey (2002) reported significant interaction effects of forearm angles and elbow angles on maximum forearm strength. Kong (2014) revealed significant interaction effects of shoulder flexion and elbow flexion on muscle activity of the upper limb and grip force. Khan, O'Sullivan, and Gallwey (2010) and Khan, O'Sullivan, and Gallwey (2009) observed a significant interaction of forearm rotation and wrist flexion on subjective discomfort. Furthermore, Lim, Jung, and Kong (2011) showed significant interaction of shoulder flexion and trunk inclination on muscle activity and subjective discomfort.

To summarise, the current situation of ergonomic analyses is characterised by a large number of methods to identify musculoskeletal load. Nevertheless, MSDs are still significant worldwide (Brandl, Mertens, and Schlick 2017a; Widanarko et al. 2012; Widanarko et al. 2011; Vos et al. 2017). For example, among industrial workers, the lower back and shoulder are most affected by MSD (Grobler 2013; Sood et al. 2017; National Academies Press (US)) 2001; Sukadarin et al. 2016). Therefore, ergonomic methods need to be further developed to make the reduction of musculoskeletal load appropriate by using such methods. A consideration of interaction effects, in particular between back and shoulder, would contribute towards this aim (Lim, Jung, and Kong 2011).

Thus, the aims of this paper are as follows: (1) investigation of musculoskeletal exposure data of the trunk and the shoulder for interaction effects, as these are the body regions most affected by MSD, (2) development of a prediction model of muscle activity under consideration of interaction effects of trunk inclination and shoulder flexion. Based on the findings of O'Sullivan and Gallwey (2002), Khan, O'Sullivan, and Gallwey (2009), Khan, O'Sullivan, and Gallwey (2010) and Lim, Jung, and Kong (2011) we hypothesised a significant interaction of trunk inclination and shoulder flexion on musculoskeletal load.

2. Method

2.1. Participants

An opportunity sample of 47 persons (29 males) participated in the current investigation. The sample was not gender-balanced, since gender-specific differences in muscle activity are not to be expected (Srinivasan et al. 2016). Musculoskeletal injury in the back, neck and shoulder during the last six months was selected as criterion of exclusion and was obtained prior to participating in this study. Consequently, 47 persons with a mean (SD) age of 25.62 years (4.07 years) and stature of 176.2 cm (10.8 cm) participated in this study. Informed written consent was obtained prior to participating in the experiment.

2.2. Experimental design

A 4 (trunk inclination) × 4 (arm lifting angle) within-subject design was devised, whereby trunk inclination and arm lifting were modified in increments of +20°

and +30°, respectively. This resulted in 16 different working postures (see Figure 1). Each posture is composed of straight legs, upright head, ventral trunk inclination of an angle between 0 and 60° and arm lifting of an angle between 0 and 90°. Trunk inclination angle was measured between the frontal plane and the longitudinal axis of the trunk, while arm angle was measured between the frontal plane and the upper arm. The participants were instructed to pose statically at 16 distinctive postures for 60 seconds each. In order to avoid a long study duration, working postures with arms above shoulder level were not investigated, as these only occur to a limited extent in industrial work (Väyrynen, Pekkarinen, and Tornberg 1994; Brandl, Mertens, and Schlick 2017b). The order of experimental conditions for each participant was permutated to reduce order effects.

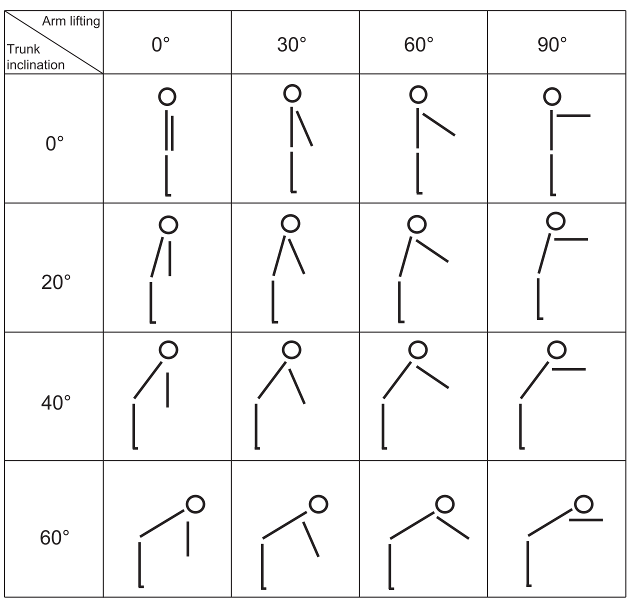

Figure 1. Static work postures resulted from combinations of trunk inclinations angles (0, 20, 40, and 60) and arm lifting angles (0, 30, 60, and 90).

As dependent variables, muscle activity of eight muscles and ratings of perceived exertion were collected. While maintaining working postures, muscle activity was sampled from the following muscles by using surface electromyography (EMG): right and left trapezius pars descendens (LUT/RUT), right and left trapezius pars ascendens (LLT/RLT), right and left anterior deltoideus (LAD/RAD), right and left erector spinae longissimus (LES/RES). The selected muscles are depicted in Figure 2. The selection of the LUT/RUT and LLT/RLT was based on their roles as shoulder stabilisers and arm activators (Kadefors et al. 1999), while the LAD/RAD were selected for their supporting roles in upper limb posture (Roman-Liu and Tokarski 2005). LES/RES were chosen as representative muscles of the back which are responsible for extension of the trunk (Hermens 1999). To eliminate muscle fatigue, after each working posture, a one-minute resting period was granted to the participants and a five-minute resting period after four working postures. Previous studies have also used these time intervals as they were sufficient to eliminate muscle fatigue (Kee and Karwowski 2001b; Genaidy and Karwowski 1993; Genaidy, Barkawi, and Christensen 1995).

Since working postures influence perceived exertion significantly (Kee and Karwowski 2001a), each participant assessed ratings of perceived exertion (RPE) regarding the whole body in each working posture. Borg's category ratio scale (Borg 1990) was employed to gather RPE.

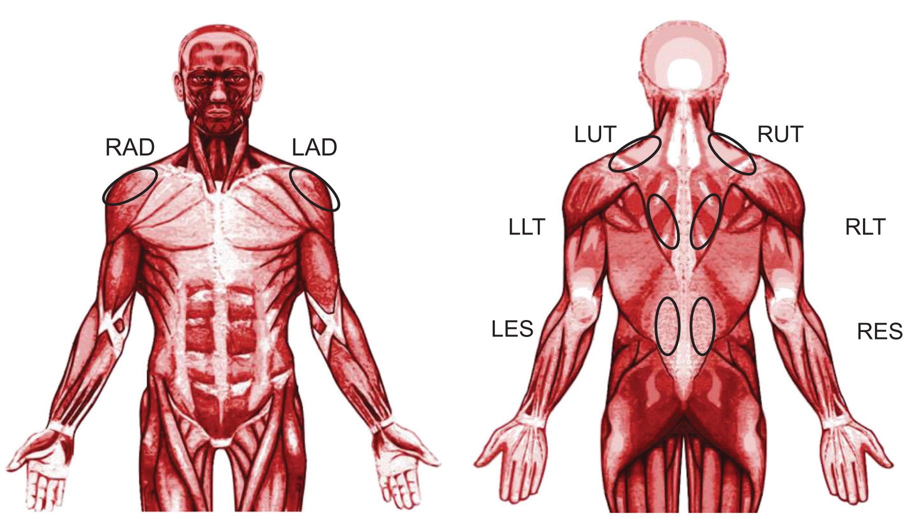

Figure 2. The eight selected muscles for electromyography analysis of the muscle activity: left and right trapezius pars descendens (LUT/RUT), left and right trapezius pars ascendens (LLT/RLT), left and right anterior deltoideus (LAD/RAD), left and right erector spinae longissimus (LES/RES).

2.3. Procedure

The experimental procedure involved two phases: (1) preparation and (2) investigation of 16 different postures.

During the first phase, participants were prepared for the sampling of EMG signals by a sensor and electrode placement procedure in accordance with SENIAM (Hermens 1999). To ensure good signal quality, participants' skin was prepared by hair removal and cleaning of the skin using an abrasive paste.

Prior to the second phase, maximal voluntary contraction (MVC) was obtained for each muscle as reference contraction. The MVC tests were performed for each investigated muscle separately. For extremity muscles (LUT/RUT, LLT/RLT, LAD/RAD) isolated isometric contractions were held statically by the use of a utility bench and belts. Details can be found in the publication of Konrad (2011). For the trunk muscles, LES/RES innervations of the muscle chain of the back by an isometric contraction was used. Since obtained MVC could be 20-30% less than MVC obtained after short training intervals, an initial warm up sequence and a test of MVC innervation were conducted before obtaining MVC values.

EMG signal detected by electrodes depends on various factors, i.e. muscle fibre type, diameter of electrodes, distance between the muscle and the electrode by tissue width (Burden and Bartlett 1999). Therefore, to compare muscle activity between different muscles, different individuals and across time the EMG signal should be normalised. In this study, isometric MVC normalisation was used according to the guidelines of SENIAM (Hermens 1999).

During the second phase of the experiment, participants were guided in holding 16 different working postures. The accuracy of the working postures was monitored by appropriate software to show real-time trunk inclination angle and arm angle using a Kinect Sensor (Kinect V2, Microsoft, WA, USA). Therefore, the coordinates of the joint positions of the skeleton model of Kinect V2 were captured as input variables to calculate trunk inclination angle and arm angle. Corresponding trigonometric equation to calculate trunk inclination angle and arm angle are described by Brandl (2017). The use of trigonometric equations is necessary to calculate trunk inclination angle and arm angle by use of the 3 D coordinates of centre points of the human body joints. For example, the calculation of the trunk inclination is based on the centre point of the left and right shoulder centre point (on the spine at C7/T1) and the hip centre (on the spine at L5/S1). Since static postures are never completely static, a permissible angle range of $\pm 5°$ was defined. If participants were close to exceeding this permissible range they were instructed by the research experimenter verbally to adjust their posture, who permanently monitored the body angles displayed by the software in real-time. The measurement of muscle activity (60 seconds) was started at the moment participants had assumed the corresponding working posture.

Throughout the initial development for video games, the Kinect has been applied during several scientific investigations, for example, Auvinet et al. (2015) conducted gait analyses, Diego-Mas and Alcaide-Marzal (2014), Patrizi, Pennestrì, and Valentini (2016) and Manghisi et al. (2017) conducted ergonomic studies. Furthermore, Plantard et al. (2017), Plantard et al. (2015) and Xu et al. (2017) evaluated accuracy of posture data captured by the Kinect. It has been shown, that the error of coordinates of the joint positions is dependent on the position of the Kinect relative to the captured person. Therefore, in this study according to Gonzalez-Jorge et al. (2015), Plantard et al. (2017), Plantard et al. (2015) and Xu et al. (2017) the Kinect was placed in front of the participants at a height of 1.2 m above the ground to avoid the shoulder being covered by the arm. Clark et al. (2012) investigated the validity of the Microsoft Kinect and revealed an ecellent concurrent validity between the Microsoft Kinect and the 3 D motion analysis system of Vicon Nexus V1.5.2 (VICON, UK). Yang et al. (2015) evaluated the accuracy of the Microsoft Kinect and showed different accuracy depending on the distance to the sensor. Therefore, in this study participants were placed within an area, which has an accuracy error of less than 2 mm. Furthermore, a sampling frequency of 30 Hz of the Kinect enables an immediate detection of postural changes during the test conditions (Yang et al. 2015). To summarise, the average error of the Kinevt has a negligible impact on our data. Therefore, the Kinect is appropriate for use in the context of investigating body postures during constant conditions in a laboratory environment.

2.4. Data recording and processing

In this experimental procedure, an EMG device (Desktop DTS Receiver, Noraxon, AZ, USA) was used to measure bilateral muscle activity of eight muscles. Ag/AgCl self-adhesive 8-shaped dual electrodes (dimensions of adhesive: 4×2.2 cm; diameter of the two circular adhesives: 1 cm; inter-electrode distance: 1.75 cm) were used. Signals were amplified with a gain of 1,000 V/V, input impedance of 100 MΩ and a common mode rejection ratio of 100 dB. Signals were sampled with a sampling frequency of 1,500 Hz and digitally band-pass filtered (10-500 Hz) with a first-order high-pass filter. Signals were recorded using the analysis software MyoResearch 3.8 (Noraxon, Scottsdale, AZ, USA). Root mean square (RMS) amplitude was calculated with an overlapping moving window of 100 ms (Hermens 1999). In order to compare EMG data for different conditions of working postures, RMS values were normalised to percent muscle activation by using the peak of the corresponding MVC reference contraction obtained prior to the experiment in accordance with SENIAM (Hermens 1999; Sousa and Tavares 2012).

2.5. Data analysis

All statistical analyses were conducted using IBM SPSS Statistics 25. A repeated-measures multivariate analysis of variance (MANOVA) was used to identify the effects of trunk inclination and shoulder flexion on muscle activity of eight muscles and RPE. The test statistic Pillai's trace was chosen, as it is considered to have the least error and to be most powerful and most robust (Field 2017), results of Pilla's trace are given as V notation. To investigate effects of different factor combinations, separate univariate *post-hoc* ANOVAs were conducted. Where the assumption of sphericity was violated, p-values were ascertained based on degrees of freedom with Greenhouse–Geisser correction (for $\varepsilon < 0.75$) (Greenhouse and Geisser 1959). Significance was accepted at the α-level of $p < 0.05$.

To develop a prediction model of muscle activity, stepwise multiple regression was employed by means of trunk inclination angle and arm angle as predictor variables and muscle activity and RPE as outcome variables. The order of predictors entered into the model was theory-based on a pre-study (Hellig, Mertens, and Brandl 2018), which first identified interaction effects of trunk inclination and arm lifting. As a result, nine regression models (eight muscles and RPE) depending on two predictor variables were calculated in the form of:

$$y_k = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m + \varepsilon \quad (1)$$

where x_s, β_s and ε represent the predictors, coefficients and residuals of k models, respectively.

To meet the assumption of linearity, polynomial relationships of the predictor variables and the outcome variables were linearised. Equations were evaluated using determination coefficients (adjusted R^2), which were interpreted as trivial (<0.02), small (0.02–<0.13), medium (0.13–<0.25) and large (>0.25) effects according to Cohen (1992). Since repeated measures data have an effect on the results derived from ordinary least squares (OLS) regression that are employed in this study, assumptions of independent residuals and homoscedasticity are violated (Donner 1984). To investigate the violation of these assumptions, the Durbin-Watson test (Durbin and Watson 1951) and Breusch–Pagan test (Breusch and Pagan 1979) were used. While model parameters are not affected by violations of independent residuals and homoscedasticity (Field 2017), significance tests and standard error estimates are affected (Donner 1984; Hayes and Cai 2007; Field 2017). Therefore, heteroscedasticity-consistent standard error estimators according to Hayes and Cai (2007) and White (1980) were employed to reduce the effects of heteroscedasticity and autocorrelation.

3. Results

3.1. Effects of trunk inclination angle and arm lifting on exertion

3.1.1. Repeated-measures MANOVA

Repeated-measures MANOVA was employed to investigate the effects of ventral trunk inclination and arm lifting on muscle activity and RPE. Trunk inclination was found to have a significant effect on muscle activity of all eight muscles and RPE, $V = 1.208$, $F(27, 396) = 9.886$, $p < 0.001$. Arm lifting was found to have a significant effect on muscle activity of all eight muscles and RPE, $V = 1.367$, $F(27, 396) = 12.276$, $p < 0.001$, and trunk inclination and arm lifting were found to have a significant interaction effect on muscle activity of all eight muscles and RPE, $V = 0.855$, $F(81, 3726) = 4.830$, $p < 0.001$.

To eliminate the influence of muscle fatigue, factor levels had been permutated. Multivariate analysis of covariance (MANCOVA) was used to detect order effects of factor levels as a between-subject factor. The order of factor levels was not found to be a significant covariate ($V = 0.195$, $F(8, 38) = 1.148$, $p = 0.355$).

Separate univariate ANOVAs were conducted *post-hoc* to investigate effects of the independent variables on muscle activity and RPE. Interaction effects of trunk inclination and arm lifting revealed a significant influence on muscle activity of LUT, RUT, LLT, RLT, LES and RES as well as on RPE. No significant influence of interaction effects was found on muscle activity of LAD and RAD. Statistics are presented in Table 1.

The significant interaction of the two factors trunk inclination and arm lifting on the muscle activity and RPE confirms the thesis that musculoskeletal load is dependent on the interaction effects of body segment postures. Since research has shown an increase of MSD symptoms in correlation with increased muscle activity (Ferguson et al. 2012; Ostensvik, Veiersted, and

Table 1. Results of univariate ANOVAs for effects of trunk inclination angle, arm lifting angle and trunk inclination angle × arm lifting angle.

Independent variable	Dependent variable	F	df1	df2	p	ηp²
Trunk inclination angle	LUT	54.2	1.9	85.6	<0.001	0.541
	RUT	43.2	1.4	65.4	<0.001	0.485
	LLT	68.4	1.4	64.6	<0.001	0.598
	RLT	136.7	1.6	75.2	<0.001	0.748
	LAD	8.4	1.9	85.8	0.001	0.154
	RAD	7.0	1.6	72.2	0.004	0.132
	LES	30.0	2.0	92.9	<0.001	0.395
	RES	26.8	2.1	94.3	<0.001	0.368
	RPE	108.0	2.2	99.5	<0.001	0.701
Shoulder flexion angle	LUT	152.1	1.6	71.4	<0.001	0.768
	RUT	156.8	1.4	65.8	<0.001	0.773
	LLT	172.8	1.4	66.2	<0.001	0.79
	RLT	218.3	2.0	92.0	<0.001	0.826
	LAD	79.8	1.6	75.5	<0.001	0.634
	RAD	98.8	1.6	75.8	<0.001	0.682
	LES	172.6	1.6	74.8	<0.001	0.79
	RES	162.0	1.6	72.4	<0.001	0.779
	RPE	336.8	2.1	96.7	<0.001	0.88
Trunk inclination angle × shoulder flexion angle	LUT	35.5	3.6	163.8	<0.001	0.436
	RUT	38.6	2.9	133.5	<0.001	0.456
	LLT	44.2	4.0	185.4	<0.001	0.49
	RLT	19.1	3.8	175.9	<0.001	0.293
	LAD	0.7	4.5	204.8	0.585	0.016
	RAD	2.3	4.0	183.9	0.059	0.048
	LES	11.2	5.2	240.0	<0.001	0.196
	RES	7.2	5.1	234.2	<0.001	0.135
	RPE	12.7	6.6	302.0	<0.001	0.216

Note: SS: sum of squares; MS: mean squares; LUT: left upper trapezius; RUT: right upper trapezius; LLT: left lower trapezius; RLT: right lower trapezius; LAD: left anterior deltoideus; RAD: right anterior deltoideus; LES: left erector spinae; RES: right erector spinae; RPE: rating of perceived exertion.

Nilsen 2009), the results indicate a considerable influence of interaction effects on MSD.

3.1.2. EMG amplitude and RPE

The interaction of trunk inclination and arm lifting on muscle activity of LUT and RUT is significant (p_{LUT} <0.001, p_{RUT} <0.001). As evident in Figure 3(a), averaged muscle activity of LUT and RUT increases with an increasing trunk inclination angle and increasing arm angle. For smaller trunk inclination angles and arm angles, there is a smaller interaction effect on muscle activity. However, interaction effects on muscle activity increase with increasing angles of trunk inclination and arm lifting.

The interaction effect of trunk inclination and arm lifting on muscle activity of LLT and RLT is significant (p_{LLT} <0.001, p_{RLT} <0.001). Figure 3(b) displays averaged muscle activity of LLT and RLT. It is evident that arm lifting influences the relationship between trunk inclination angle and muscle activity and vice versa. The interaction increases for increasing trunk inclination angle and increasing arm angle.

Muscle activity of LAD and RAD did not show a significant influence of an interaction of trunk inclination and arm lifting ($p_{LAD} = 0.585$, $p_{RAD} = 0.059$). The influence of arm lifting on muscle activity of LAD and RAD ($p_{LAD} <$ 0.001, $p_{RAD} < 0.001$; $\eta^2_{LAD} = 0.634$, $\eta^2_{RAD} = 0.682$) is greater than the influence of trunk inclination on muscle activity of LAD and RAD ($p_{LAD} = 0.001$, $p_{RAD} = 0.004$; $\eta^2_{LAD} = 0.154$, $\eta^2_{RAD} = 0.132$). The relationship between trunk inclination, arm lifting and muscle activity is displayed in Figure 3(c). In contrast to the course of muscle activity of LUT, RUT, LLT and RLT the course of muscle activity of LAD and RAD follows a quadratic function.

The interaction effect of trunk inclination and arm lifting on muscle activity of LES and RES was statistically significant ($p_{LES} < 0.001$, $p_{RES} < 0.001$). As evident from Figure 3(d) muscle activity of LES and RES follows a quadratic function.

The interaction effect of trunk inclination and arm lifting on RPE was significant ($p_{RPE} < .001$). The relationship between trunk inclination, arm lifting and RPE is shown in Figure 4. Despite the significant interaction of the factors on RPE the curves in Figure 4 show the same trend. Due to the investigation of all individual values obtained during the investigation by the conducted ANOVA, significant interaction effects may occure despite the lack of overlapping curves. This is possible due to the overlapping of the error bars of the standard deviations, as it can be observed in Figure 4. For increasing trunk inclination angles, RPE shows an increase for all arm angles.

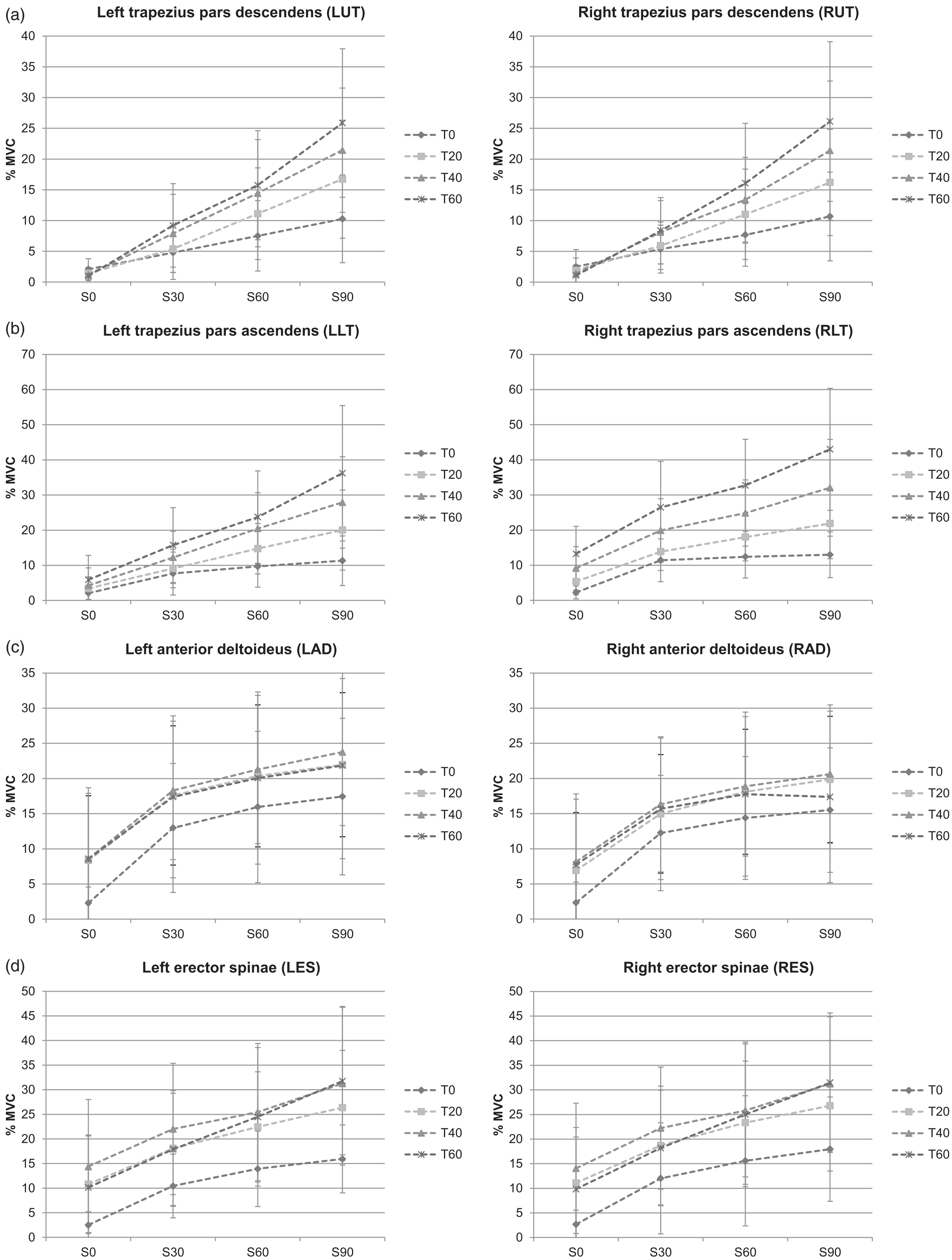

Figure 3. Averaged muscle activity according to trunk inclination angle (T) and arm lifting angle (S).

3.2. Regression equations

Stepwise multiple regression analysis was used to assess quantitative relationships between levels of trunk inclination angle and arm angle as well as muscle activity and RPE. Final results of predicting models are presented in Table 2. The Breusch-Pagan test of homoscedasticity revealed significance for all

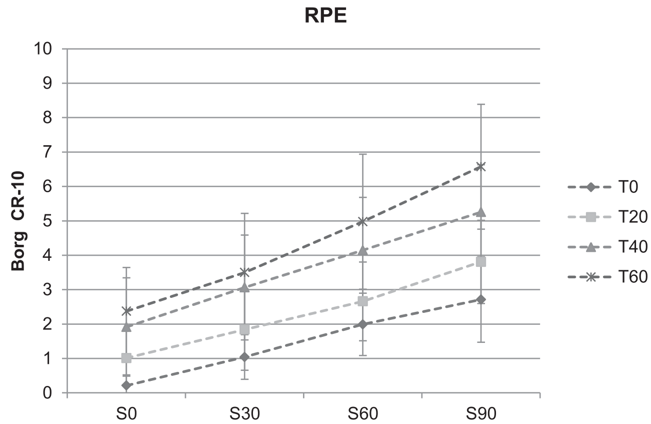

Figure 4. Averaged RPE according to trunk inclination angle (T) and arm lifting angle (S), error bars.

Table 2. Output of final regression equations for predicting muscle activity and RPE.

OV	PVs	β_0	β_1 (T^2)	β_2 (S^2)	β_3 (T)	β_4 (S)	β_5 (T × S)	Sig.	Adj. R^2	F	df1	df2	SEE
LUT	S^2, T^2, T × S	−0.099	−0.394	0.276			1.719	<0.001	0.525	434.323	3.0	748.0	6.853
RUT	S^2, T^2, T × S	0.319	−0.423	0.256			1.722	<0.001	0.519	165.983	3.0	748.0	6.792
LLT	S, T, T × S	0.796			0.222	0.211	2.629	<0.001	0.603	276.074	3.0	748.0	9.136
RLT	S, T, T × S	−0.333			1.222	1.225	2.071	<0.001	0.550	255.649	3.0	748.0	9.479
LAD	S^2, T^2	7.964	0.251	0.827				<0.001	0.174	77.09	2.0	749.0	10.723
RAD	S^2, T^2	7.615	0.184	0.691				<0.001	0.147	62.614	2.0	749.0	9.727
LES	T^2, S^2, T × S	8.266	−0.328	0.124			1.902	<0.001	0.277	75.965	3.0	748.0	11.808
RES	T^2, S^2, T × S	9.033	−0.351	0.209			1.785	<0.001	0.264	78.253	3.0	748.0	12.006
RPE	S^2, T^2, T × S	−1.027			0.516	0.601	0.188	<0.001	0.608	467.532	3.0	748.0	1.320

Note: OV: outcome variable; PVs: predictor variables; β: coefficients; T: trunk inclination angle; S: arm lifting angle; SEE: standard error estimator; LUT: left upper trapezius; RUT: right upper trapezius; LLT: left lower trapezius; RLT: right lower trapezius; LAD: left anterior deltoideus; RAD: right anterior deltoideus; LES: left erector spinae; RES: right erector spinae; RPE: rating of perceived exertion.

muscles and RPE. The Durbin-Watson test indicated a violation of independent errors for all muscles and RPE. Therefore, heteroscedasticity-consistent and corrected standard error estimates according to Hayes and Cai (2007) were used. All predictors of each model shown in Table 2 revealed significance. Since, in addition to linear relationships between the predictor variables and the outcome variables, there are also quadratic and interaction relationships, each model contains more than two coefficients.

3.2.1. Upper trapezius

Muscle activity of LUT and RUT shows a quadratic dependence on trunk inclination angle and arm angle. Based on previous studies, the influence of arm angle on LUT/RUT tended to be higher. Therefore, arm lifting was entered first in the models of LUT and RUT. Based on the significant interaction of trunk inclination angle and arm angle, an interaction term is included in the model as well. The final models for predicting muscle activity of LUT and RUT were significant (p<.001). The models explained more than 50% of the total variance.

3.2.2. Lower trapezius

The relationships between LLT and RLT and trunk inclination angle and arm angle, respectively, were found to be linear. Based on previous findings, the influence of arm angle on LLT and RLT was found to be higher. Therefore, arm lifting was entered first in the models of LLT and RLT. Based on the significant interaction of trunk inclination angle and arm angle an interaction term is included in the model as well. The final models for predicting muscle activity of LLT and RLT revealed significance (p<.001). The model of LLT explained 60% of the total variance, the model of RLT explained 55% of the total variance.

3.2.3. Anterior deltoid

Muscle activity of LAD and RAD show a quadratic dependence on trunk inclination angle and arm angle. Based on a pre-study, the influence of arm angle on LAD/RAD tended to be higher. Therefore, arm lifting was entered first in the models of LAD and RAD. Since there was no significant interaction of trunk inclination angle and arm angle on LAD and RAD, an interaction term is not included in the model. The final models for predicting muscle activity of LAD and RAD revealed significance ($p < 0.001$). The models explained less than 20% of the total variance.

3.2.4. Erector spinae

Muscle activity of LES and RES show a quadratic dependence on trunk inclination angle and arm angle. Based on previous findings, the influence of trunk inclination angle on LES and RES was found to be higher. Therefore, trunk inclination angle was entered first in the models of LES and RES. Based on the significant interaction of trunk inclination angle and arm angle an interaction term is included in the model as well. The final models for predicting muscle activity of LES and RES revealed significance ($p < 0.001$). The models of LES and RES explained more than 25% of the total variance.

3.2.5. Perceived exertion

Investigation of the relationships between RPE and trunk inclination angle and arm angle revealed them to be linear. Based on previous findings, the influence of arm angle on RPE was found to be higher. Therefore, arm lifting was entered first in the model of RPE. Based on the significant interaction of trunk inclination angle and arm angle an interaction term is included in the model as well. The final model for predicting RPE revealed significance ($p < 0.001$). The model of RPE explained 60% of the total variance.

4. Discussion

The purpose of this study was to investigate empirical data of interaction effects of working postures and to derive a quantitative approach to describe changes in muscle activity and RPE. Previous studies conducted investigations of several parameters influencing musculoskeletal exposure, for example, joint angles, duration and frequency of exposure time or grip force, e.g. Bosch et al. (2012), Burdorf (1992), Farooq and Khan (2012) or O'Sullivan and Gallwey (2002). However, only a small number investigated interaction effects of working postures in a systematic way. This study revealed significant interaction effects of working postures on muscle activity and RPE.

Our findings are in line with those of Lim, Jung, and Kong (2011), who investigated upper-limb working postures related to trunk inclination and arm lifting and stated significant effects on several muscles like ES, UT, LT and AD. However, to our knowledge no further investigations of trunk inclination and arm lifting on muscle activity have been conducted so far. Results of Hellig, Mertens, and Brandl (2018) showed that muscle activity in the shoulder depends on arm lifting angle between the frontal plane and the upper arm, since muscle activity is highly dependent on the lever arm between the load and the joint pivot in the shoulder. Therefore, an increase in arm angle causes an increase in muscle activity of the shoulder muscles UT and LT. The effect of an interaction between trunk inclination and arm lifting is shown in muscle activity of the shoulder muscles as an increasing trunk inclination decreases muscle activity of UT and LT even for large arm angles. The reason for this effect can be found in the increasing blood flow of shoulder muscles during increased trunk inclination. The increased trunk inclination leads to a decreased height of the upper arm and an increased oxygen supply of the muscles UT and LT. This reduces the metabolism of the muscle and thus muscle activity (Lin et al. 2010).

An increase of trunk inclination has an increasing effect on muscle activity of the ES. As the function of the ES allows the trunk to be upright against gravity by a contraction of ES, muscle activity of ES depends on the lever arm between the load and the pivot of the back and, consequently, the torque generated by the load (Jäger and Luttmann 1989). Therefore, an increase of muscle activity of ES can be found for increasing trunk inclination. Furthermore, for an increase of trunk inclination from 40° to 60° a decreasing muscle activity was found. The increase in abdominal oressure can be considered as major effect for this course of muscle activity in ES (Jäger and Luttmann 1989). Therefore, our results extend those of Sakamoto and Swie (2003), who investigated muscle activity of the ES and the lower limb in dependence on the single factor trunk inclination angle, which was varied between 0 and 180°. Sakamoto and Swie (2003) reported an increasing muscle activity of ES with increasing trunk inclination angle, which reached maximum activity at 90° trunk inclination.

The second purpose of this study was to describe the relationship between body posture angles and musculoskeletal load quantitatively. For this purpose, a regression model for the prediction of muscle activity and RPE was developed. The determination coefficients of the regression equations ranged from medium ($R^2 = 0.147$) to large ($R^2 = 0.608$). Determination coefficients (adjusted R^2) were interpreted as trivial (<0.02), small (0.02–<0.13), medium (0.13–<0.25) and large (>0.25) effects according to Cohen (1992). A medium degree of variance in muscle activity of LAD ($R^2 = 0.174$) and RAD ($R^2 = 0.147$) as well as LES ($R^2 = 0.277$) and RES ($R^2 = 0.264$) is explained by the factors trunk inclination angle and arm angle. Hence, other factors influencing muscle activity of LAD and RAD as well as LES and RES seem to apply. Since experimental conditions were kept constant, personal factors influencing muscle activity are plausible, such as physical fitness level influencing relative personal strength in relation to maximum voluntary contraction or anthropometry. Nevertheless, regression equations of LAD, RAD, LES and RES were found to be statistically significant, which indicates that regression equations are significantly different from zero. Since regression coefficients assess the relationship between predictor and outcome variable, an agreement of coefficients of left and right muscles emphasises the consistency of the collected data. Subsequently, the validity of derived regression equations of LAD and RAD as well as LES and RES is emphasised by this fact (see Table 2). Trunk inclination and arm lifting showed quadratic relationships to muscle activity of LAD, RAD, LES and RES. Therefore, these predictors are recognised in quadratic terms in the regression equations of muscle activity of LAD, RAD, LES and RES. A regression coefficient of nearly 1.9 and 1.8 representing interaction of trunk inclination and arm lifting in LES and RES, respectively, shows the great influence of the interaction effect on muscle activity in these muscles. It seems plausible that interaction of trunk inclination and arm lifting is caused by two lever arms and, consequently, an increased torque generated by these lever arms. In contrast, the small coefficients of trunk inclination and arm lifting show a very small influence of these factors on muscle activity. This is further evidence of the high relevance of interaction effects on musculoskeletal load.

Determination coefficients of LUT ($R^2 = 0.525$) and RUT ($R^2 = 0.519$) are large. Therefore, a relatively high amount of variance in muscle activity of LUT and RUT is explained by the factors trunk inclination angle and arm angle and their interaction. Regression coefficient of interaction of trunk inclination and arm lifting is approximately 1.7, which indicates a great influence of interaction of these factors on muscle activity in LUT and RUT. The small coefficients of trunk inclination and arm lifting emphasise the small influence of the single factors on muscle activity in LUT and RUT. A negative coefficient of trunk inclination shows an opposite direction of the effect of trunk inclination on muscle activity on LUT and RUT. Increasing trunk inclination reduces arm height and, therefore, contributes to an increased blood flow in LUT and RUT, which decreases muscle metabolism and, consequently, decreases muscle activity. Similar effects could be observed by Lin et al. (2010), who investigated the influence of arm lifting on subjective discomfort.

Determination coefficients of LLT ($R^2 = 0.603$) and RLT ($R^2 = 0.550$) are large and, therefore, effects of trunk inclination and arm lifting and their interaction contribute extensively to explaining variance in muscle activity of LLT and RLT. Again, regression equations of LLT and RLT reached significance. The relatively high coefficients of interaction underline the great influence of interaction of trunk inclination and arm lifting on LLT and RLT.

Finally, the determination coefficient of RPE (R^2=0.608) was large, explaining a relatively high degree of variance in RPE using trunk inclination and arm lifting. In contrast to muscle activity, the interaction term of trunk inclination and arm lifting only influences RPE to a limited extent. As a limiting factor in the interpretation of RPE, consideration must be given to cognitive processes. According to Karwowski et al. (1999), significant relationships between RPE and cognitive appraisal of weights are evident. Therefore, a significant increase in RPE can be caused by the combination of large joint angles, e.g. in this study the combination of 60° trunk inclination and 90° arm lifting.

The goal of decreasing musculoskeletal load can be supported by the use of prediction equations to calculate muscle activity and RPE, i.e. during the planning phase of a new work place or during an revision phase of an existing workplace. In order to use the regression model developed in this study for an investigation of musculoskeletal injury risk, a threshold of muscle activity has to be set as a guideline. Depending on blood circulation to continue oxygen supply of the muscle, contractions of more than 15–20% MVC should be avoided (Kroemer 1989; Björkstén and Jonsson 1977). Exceeding this limit of maximum contraction would cause an internal muscle pressure which exceeds the blood pressure, leading to a shortage of oxygen in the muscle. The thresholds suggested by Kroemer (1989) and Björkstén and Jonsson (1977) were derived from an investigation of increase of inner muscle temperature. During those investigations, one leg was severely undercooled by a water bath. Subsequently, the temperature increase during different static muscle contractions were investigated. During contractions of not more than 15% MVC increasing muscle temperatures were obtained. This increase in temperature indicates an increase in blood flow through the muscle. No increase of muscle temperature could be observed during contractions of 20% MVC and above. McNeil et al. (2015) confirmed the thresholds by an investigation of blood velocity and arterial diameter with Doppler ultrasound.

Depending on observation based analyses of working postures, a calculation of arising muscle activities is possible by using the prediction equations of the introduced regression model. An increased risk must be assumed if the muscle activity of at least one muscle exceeds 15–20% MVC.

However, the introduced prediction model only provides an indication of musculoskeletal load of working postures. Further factors like load weight, force levels or cognitive influences on workload are not considered by this model.

Nevertheless, the results of our investigation show the complexity of interaction effects, even though only interaction effects of two factors were investigated. One way to simplify a consideration of interaction effects during the assessment of working postures could be an integration of our regression model into methods for an assessment of range sensor based analysis of posture data. The use of range sensors would help decrease the workload of sampling posture data and considering interaction effects would increase the reliability of the assessment results.

However, there are some limitations to this study which have to be considered in the interpretation of the results. First, only static working postures were investigated in this study. To meet the demands of use in practice, dynamic working postures have to be considered too.

The muscles investigated in this study may be considered representative of musculoskeletal load in upper limbs. However, there are arguments for and against selecting the muscles investigated in this study. Therefore, it should also be noted that the shoulder girdle is a complex area (Kadefors et al. 1999) and several muscles in this area are related to shoulder joint movement like flexion or extension (Iridiastadi, Nussbaum, and van Dieën 2008). Since the determination coefficients of LUT and RUT, as well as LLT and RLT, were found to be high, it can be assumed that muscle activity in these muscles is influenced to a significant extent by trunk inclination and arm lifting and their interaction.

Furthermore, in this study absolute values of inclination angles were used. Using absolute values and values relative to the individual range of motions is a controversial issue. Since this study tries to deliver results of practical relevance, we decided to investigate absolute values, because in practice work tasks, for example, the assembly of products or toll mounting in machinery, can usually not be aligned to the individual body dimensions of the working person.

Moreover, since polynomials of 2nd degree are used in this work, overfitting might be a danger in deriving regression equations. Since the experimental design has been changed in comparison to pre-studies, courses of muscle activity could be almost linearised and the danger of overfitting could be reduced to a minimum.

There are also limitations regarding the participants of this study. Only young persons in good physical condition were tested. Therefore, discrepancies between these young participants and people working in industry may be found. However, since industrial workers are physically fit due to their daily activities, the young and healthy participants of this study represent industrial workers adequately, despite some differences regarding motor strategies and muscle fatigue (Iridiastadi and Nussbaum 2006). Additionally, this study focussed on the investigation of static postures. However, practical relevance can be increased by the consideration of dynamic movements of body parts. Since this study is a first step towards the quantification of interaction effects, the consideration of static postures is the first step of such quantification. Finally, in this study the Kinect was used to monitor the accuracy of the investigated working postures. This may result in a slightly higher deviation from the permissible angle range of $\pm 5^{\circ}$. However, since several studies have shown a good accuracy of posture data captured by the Kinect and since the Kinect was placed according to the recommendations of several scientific study results, high data accuracy can be assumed.

5. Conclusion

This study investigated interaction effects of working postures. The results showed significant interaction of working postures on the dependent variables representing musculoskeletal and subjective load. Furthermore, a prediction model of musculoskeletal and subjective load depending on trunk inclination and arm lifting was derived. To meet the overall need to decrease MSD to a significant extent, a consideration of interaction effects of working postures is required. The need for easy-to-use methods may be achieved by the development of exposure assessment methods depending on posture data. The introduced regression model contributes towards the development of such methods.

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References

Auvinet, E., F. Multon, C.-E. Aubin, J. Meunier, and M. Raison. 2015. "Detection of Gait Cycles in Treadmill Walking Using a Kinect." *Gait and Posture* 41 (2): 722–725. doi:10.1016/j.gaitpost.2014.08.006.

Björkstén, M., and B. Jonsson. 1977. "Endurance Limit of Force in Long-Term Intermittent Static Contractions." *Scandinavian Journal of Work, Environment and Health* 3 (1): 23–27. doi:10.5271/sjweh.2795.

Borg, G. 1990. "Psychophysical Scaling with Applications in Physical Work and the Perception of Exertion." *Scandinavian Journal of Work, Environment and Health* 16 (Suppl 1): 55–58. doi:10.5271/sjweh.1815.

Bosch, T., S. E. Mathiassen, D. Hallman, M. P. de Looze, E. Lyskov, B. Visser, and J. H. van Dieën. 2012. "Temporal Strategy and Performance during a Fatiguing Short-Cycle Repetitive Task." In: *Ergonomics* 55 (8): 863–873. doi:10.1080/00140139.2012.682739.

Brandl, C.. 2017. "Ergonomische Analyse von Körperhaltungen in Produktionssystemen für eine computergestützte Arbeitsgestaltung und -organisation" [Ergonomic Analysis of Working Postures in Production Systems for Computer-Aided Industrial Engineering]. Dissertation, RWTH Aachen, Aachen.

Brandl, C., A. Mertens, and C. M. Schlick. 2017a. "Effect of Sampling Interval on the Reliability of Ergonomic Analysis Using the Ovako Working Posture Analysing System (OWAS)." *International Journal of Industrial Ergonomics* 57: 68–73. doi:10.1016/j.ergon.2016.11.013.

Brandl, C., A. Mertens, and C. M. Schlick. 2017b. "Ergonomic Analysis of Working Postures Using OWAS in Semi-Trailer Assembly, Applying an Individual Sampling Strategy." In: *International Journal of Occupational Safety and Ergonomics* 23 (1): 1–8. doi:10.1080/10803548.2016.1191224.

Breusch, T. S., and A. R. Pagan. 1979. "A Simple Test for Heteroscedasticity and Random Coefficient Variation." *Econometrica* 47 (5): 1287. doi:10.2307/1911963.

Burden, A., and R. Bartlett. 1999. "Normalisation of EMG Amplitude. An Evaluation and Comparison of Old and New Methods." *Medical Engineering and Physics* 21 (4): 247–257. doi:10.1016/S1350-4533(99)00054-5.

Burdorf, A. 1992. "Exposure Assessment of Risk Factors for Disorders of the Back in Occupational Epidemiology." *Scandinavian Journal of Work, Environment and Health* 18 (1): 1–9. doi:10.5271/sjweh.1615.

Clark, R. A., Y.-H. Pua, K. Fortin, C. Ritchie, K. E. Webster, L. Denehy, and A. L. Bryant. 2012. "Validity of the Microsoft Kinect for Assessment of Postural Control." *Gait and Posture* 36 (3): 372–377. doi:10.1016/j.gaitpost.2012.03.033.

Cohen, J. 1992. "A Power Primer." *Psychological Bulletin* 112 (1): 155–159. doi:10.1037/0033-2909.112.1.155.

David, G. C. 2005. "Ergonomic Methods for Assessing Exposure to Risk Factors for Work-Related Musculoskeletal Disorders." *Occupational Medicine* 55 (3): 190–199. doi:10.1093/occmed/kqi082.

Denis, D., M. Lortie, and M. Rossignol. 2000. "Observation Procedures Characterizing Occupational Physical Activities. Critical Review." *International Journal of Occupational Safety and Ergonomics* 6 (4): 463–491. doi:10.1080/10803548.2000.11076467.

Diego-Mas, Jose, and Jorge Antonio; Alcaide-Marzal. 2014. "Using Kinect™ Sensor in Observational Methods for Assessing Postures at Work." *Applied Ergonomics* 45 (4): 976–985. doi:10.1016/j.apergo.2013.12.001.

Donner, Allan. 1984. "Linear Regression Analysis with Repeated Measurements." *Journal of Chronic Diseases* 37 (6): 441–448. doi:10.1016/0021-9681(84)90027-4.

Durbin, J., and G. S. Watson. 1951. "Testing for Serial Correlation in Least Squares Regression. II." *Biometrika* 38 (1–2): 159–178. doi:10.1093/biomet/38.1-2.159.

EN 1005-4. 2009. 01: Safety of Machinery – Human Physical Performance – Part 4: Evaluation of Working Postures and Movements in Relation to Machinery.

Farooq, M., and A. A. Khan. 2012. "Effect of Elbow Flexion, Forearm Rotation and Upper Arm Abduction on MVC Grip and Grip Endurance Time." *International Journal of Occupational Safety and Ergonomics* 18 (4): 487–498. doi:10.1080/10803548.2012.11076955.

Ferguson, S. A., W. S. Marras, W. G. Allread, G. G. Knapik, and R. E. Splittstoesser. 2012. "Musculoskeletal Disorder Risk during Automotive Assembly. Current vs. seated." *Applied Ergonomics* 43 (4): 671–678. doi:10.1016/j.apergo.2011.10.001.

Field, A. P. 2017. *Discovering Statistics Using IBM SPSS Statistics*. 5th ed. London: Sage.

Genaidy, A. M., and W. Karwowski. 1993. "The Effects of Neutral Posture Deviations on Perceived Joint Discomfort Ratings in Sitting and Standing Postures." *Ergonomics* 36 (7): 785–792. doi:10.1080/00140139308967942.

Genaidy, A., H. Barkawi, and D. Christensen. 1995. "Ranking of Static Non-Neutral Postures around the Joints of the Upper Extremity and the Spine." *Ergonomics* 38 (9): 1851–1858. doi:10.1080/00140139508925232.

Gonzalez-Jorge, H., P. Rodríguez-Gonzálvez, J. Martínez-Sánchez, D. González-Aguilera, P. Arias, M. Gesto, and L. Díaz-Vilariño. 2015. "Metrological Comparison between Kinect I and Kinect II Sensors." *Measurement* 70: 21–26. doi:10.1016/j.measurement.2015.03.042.

Greenhouse, S. W., and S. Geisser. 1959. "On Methods in the Analysis of Profile Data." *Psychometrika* 24 (2): 95–112. doi:10.1007/BF02289823.

Grobler, C. J. 2013. "Self-Reported Work-Related Musculoskeletal Injuries and Isometric Handgrip Strength." *Occupational Medicine* 63 (3): 210–216. doi:10.1093/occmed/kqt007.

Hayes, A. F., and L. Cai. 2007. "Using Heteroskedasticity-Consistent Standard Error Estimators in OLS Regression. An Introduction and Software Implementation." *Behavior Research Methods* 39 (4): 709–722. doi:10.3758/BF03192961.

Hellig, T., A. Mertens, and C. Brandl. 2018. "The Interaction Effect of Working Postures on Muscle Activity and Subjective Discomfort during Static Working Postures and Its Correlation with OWAS." *International Journal of Industrial Ergonomics* 68: 25–33. doi:10.1016/j.ergon.2018.06.006.

Hermens, H. J. 1999. "European Recommendations for Surface ElectroMyoGraphy: Results of the SENIAM Project." *Enschede: Roessingh Research and Development* (SENIAM) 8.

Hignett, S., and L. McAtamney. 2000. "Rapid Entire Body Assessment (REBA)." *Applied Ergonomics* 31 (2): 201–205. doi:10.1016/S0003-6870(99)00039-3.

Iridiastadi, H., and M. A. Nussbaum. 2006. "Muscle Fatigue and Endurance during Repetitive Intermittent Static Efforts. Development of Prediction Models." *Ergonomics* 49 (4): 344–360. doi:10.1080/00140130500475666.

Iridiastadi, H., M. A. Nussbaum, and J. H. van Dieën. 2008. "Muscular Load Characterization during Isometric Shoulder Abductions with Varying Force." *Journal of Electromyography and Kinesiology* 18 (4): 695–703. doi:10.1016/j.jelekin.2007.01.011.

Jäger, M., and A. Luttmann. 1989. "Biomechanical Analysis and Assessment of Lumbar Stress during Load Lifting Using a Dynamic 19-Segment Human Model." *Ergonomics* 32 (1): 93–112. doi:10.1080/00140138908966070.

Kadefors, R., M. Forsman, B. Zoéga, and P. Herberts. 1999. "Recruitment of Low Threshold Motor-Units in the Trapezius Muscle in Different Static Arm Positions." *Ergonomics* 42 (2): 359–375. doi:10.1080/001401399185711.

Karhu, O., P. Kansi, and I. Kuorinka. 1977. "Correcting Working Postures in Industry: A Practical Method for Analysis." *Applied Ergonomics* 8 (4): 199–201. doi:10.1016/0003-6870(77)90164-8.

Karwowski, W., W. Lee, B. Jamaldin, P. Gaddie, R. L. Jang, and K. K. Alqesaimi. 1999. "Beyond Psychophysics. The Need for a Cognitive Engineering Approach to Setting Limits in Manual Lifting Tasks." *Ergonomics* 42 (1): 40–60. doi:10.1080/001401399185793.

Kee, D., and W. Karwowski. 2001a. "The Boundaries for Joint Angles of Isocomfort for Sitting and Standing Males Based on Perceived Comfort of Static Joint Postures." *Ergonomics* 44 (6): 614–648. doi:10.1080/00140130110038044.

Kee, D., and W. Karwowski. 2001b. "LUBA: An Assessment Technique for Postural Loading on the Upper Body Based on Joint Motion Discomfort and Maximum Holding Time." *Applied Ergonomics* 32 (4): 357–366. doi:10.1016/S0003-6870(01)00006-0.

Khan, A. A., L. O'Sullivan, and T. J. Gallwey. 2009. "Effects of Combined Wrist Flexion/Extension and Forearm Rotation and Two Levels of Relative Force on Discomfort." *Ergonomics* 52 (10): 1265–1275. doi:10.1080/00140130903040208.

Khan, A. A., L.O'Sullivan, and T. J. Gallwey. 2010. "Effect on Discomfort of Frequency of Wrist Exertions Combined with Wrist Articulations and Forearm Rotation." *International Journal of Industrial Ergonomics* 40 (5): 492–503. doi:10.1016/j.ergon.2010.05.003.

Kong, Y.-K. 2014. "The Effects of co-Ordinating Postures with Shoulder and Elbow Flexion Angles on Maximum Grip Strength and Upper-Limb Muscle Activity in Standing and Sitting Postures." *nternational Journal of Occupational Safety and Ergonomics* 20 (4): 595–606. doi:10.1080/10803548.2014.11077077.

Konrad, P. 2011. "The ABC of EMG – A Practical Introduction to Kinesiological Electromyography."

Kroemer, K. H. E. 1989. "Cumulative Trauma Disorders. Their Recognition and Ergonomics Measures to Avoid Them." *Applied Ergonomics* 20 (4): 274–280. doi:10.1016/0003-6870(89)90190-7.

Lim, C.-M., M.-C. Jung, and Y.-K. Kong. 2011. "Evaluation of Upper-Limb Body Postures Based on the Effects of Back and Shoulder Flexion Angles on Subjective Discomfort Ratings, Heart Rates and Muscle Activities." *Ergonomics* 54 (9): 849–857. doi:10.1080/00140139.2011.600777.

Lin, C.-L., M.-J. J. Wang, C. G. Drury, and Y.-S. Chen. 2010. "Evaluation of Perceived Discomfort in Repetitive Arm Reaching and Holding Tasks." *International Journal of Industrial Ergonomics* 40 (1): 90–96. doi:10.1016/j.ergon.2009.08.009.

Manghisi, V. M., A. E. Uva, M. Fiorentino, V. Bevilacqua, G. F. Trotta, and G. Monno. 2017. "Real Time RULA Assessment Using Kinect v2 Sensor." *Applied Ergonomics* 65: 481–491. doi:10.1016/j.apergo.2017.02.015.

McAtamney, L., and N. E. Corlett. 1993. "RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders." *Applied Ergonomics* 24 (2): 91–99. doi:10.1016/0003-6870(93)90080-S.

McNeil, C. J., M. D. Allen, E. Olympico, J. K. Shoemaker, and C. L. Rice. 2015. "Blood Flow and Muscle Oxygenation during Low, Moderate, and Maximal Sustained Isometric Contractions." *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 309 (5): R475–R481. doi:10.1152/ajpregu.00387.2014.

National Academies Press (US). 2001. *Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities*. Washington (DC): National Academy Press.

O'Sullivan, L. W., and T. J. Gallwey. 2002. "Upper-Limb Surface Electro-Myography at Maximum Supination and Pronation Torques. The Effect of Elbow and Forearm Angle." *Journal of Electromyography and Kinesiology* 12 (4): 275–285. doi:10.1016/S1050-6411(02)00014-7.

Ostensvik, T., K. B. Veiersted, and P. Nilsen. 2009. "Association between Numbers of Long Periods with Sustained Low-Level Trapezius Muscle Activity and Neck

Pain." *Ergonomics* 52 (12): 1556–1567. doi:10.1080/00140130903199889.

Patrizi, A., E. Pennestrì, and P. P. Valentini. 2016. "Comparison between Low-Cost Marker-Less and High-End Marker-Based Motion Capture Systems for the Computer-Aided Assessment of Working Ergonomics." *Ergonomics* 59 (1): 155–162. doi:10.1080/00140139.2015.1057238.

Plantard, P., E. Auvinet, A.-S. Pierres, and F. Multon. 2015. "Pose Estimation with a Kinect for Ergonomic Studies. Evaluation of the Accuracy Using a Virtual Mannequin." *Sensors* 15 (1): 1785–1803. doi:10.3390/s150101785.

Plantard, P., H. P. H. Shum, A.-S. Le Pierres, and F. Multon. 2017. "Validation of an Ergonomic Assessment Method Using Kinect Data in Real Workplace Conditions." *Applied Ergonomics* 65: 562–569. doi:10.1016/j.apergo.2016.10.015.

Roman-Liu, D., and T. Tokarski. 2005. "Upper Limb Load as a Function of Repetitive Task Parameters. Part 2–an Experimental Study." *International Journal of Occupational Safety and Ergonomics* 11 (1): 103–112. doi:10.1080/10803548.2005.11076634.

Sakamoto, K., and Y. W. Swie. 2003. "EMG Characteristics of Low Back and Lower Limb Muscles during Forward Bending Posture." *Electromyography and Clinical Neurophysiology* 43 (6): 335–347.

Sood, D., M. A. Nussbaum, K. Hager, and H. C. Nogueira. 2017. "Predicted Endurance Times during Overhead Work. Influences of Duty Cycle and Tool Mass Estimated Using Perceived Discomfort." *Ergonomics* 60 (10): 1405–1414. doi:10.1080/00140139.2017.1293850.

Sousa, A., and M. S. Tavares. 2012. "Surface Electromyographic Amplitude Normalization Methods: A Review." In *Electromyography: New Developments, Procedures and Applications*, edited by Hiroki Takada, 85–102. New York: Nova Science Publishers, Inc. (Neuroscience Research Progress).

Srinivasan, D., K. E. Sinden, S. E. Mathiassen, and J. N. Côté. 2016. "Gender Differences in Fatigability and Muscle Activity Responses to a Short-Cycle Repetitive Task." *European Journal of Applied Physiology* 116 (11–12): 2357–2365. doi:10.1007/s00421-016-3487-7.

Sukadarin, E. H., B. M. Deros, J. A. Ghani, N. S. Mohd Nawi, and A. R. Ismail. 2016. "Postural Assessment in Pen-and-Paper-Based Observational Methods and Their Associated Health Effects. A Review." *International Journal of Occupational Safety and Ergonomics* 22 (3): 389–398. doi:10.1080/10803548.2016.1156924.

Takala, E.-P., I. Pehkonen, M. Forsman, G.-Å. Hansson, S. E. Mathiassen, and W. P. Neumann. 2010. "Systematic Evaluation of Observational Methods Assessing Biomechanical Exposures at Work." *Scandinavian Journal of Work, Environment and Health* 36 (1): 3–24. doi:10.5271/sjweh.2876.

Väyrynen, S., A. Pekkarinen, and V. Tornberg. 1994. "Some Links between Accidents, Postural Load and Accessibility in Chemical Plant Maintenance." *Safety Science* 18 (2): 125–133. doi:10.1016/0925-7535(94)90021-3.

Vos, T., A. A. Abajobir, K. H. Abate, C. Abbafati, K. M. Abbas, F. Abd-Allah, R. S. Abdulkader, A. M. Abdulle, T. A. Abebo, S. F. Abera, V. Aboyans, L. J. Abu-Raddad, I. N. Ackerman, A. A. Adamu, O. Adetokunboh, M. Afarideh, A. Afshin, S. K. Agarwal, R. Aggarwal, A. Agrawal, S. Agrawal, H. Ahmadieh, M. B. Ahmed, M. T. E. Aichour, A. N. Aichour, I. Aichour, S. Aiyar, R. O. Akinyemi, N. Akseer, F. H. Al Lami, F. Alahdab, Z. Al-Aly, K. Alam, N. Alam, T. Alam, D. Alasfoor, K. A. Alene, R. Ali, R. Alizadeh-Navaei, A. Alkerwi, F. Alla, P. Allebeck, C. Allen, F. Al-Maskari, R. Al-Raddadi, U. Alsharif, S.Alsowaidi, K. A. Altirkawi, A. T. Amare, E. Amini, W. Ammar, Y. A. Amoako, H. H. Andersen, C. A. T. Antonio, P. Anwari, J. Ärnlöv, A. Artaman, K. K. Aryal, H. Asayesh, S. W. Asgedom., R. Assadi, et al. 2017. "Global, Regional, and National Incidence, Prevalence, and Years Lived with Disability for 328 Diseases and Injuries for 195 Countries, 1990–2016. A Systematic Analysis for the Global Burden of Disease Study 2016." *The Lancet* 390 (10100): 1211–1259. doi:10.1016/S0140-6736(17)32154-2.

White, H. 1980. "A Heteroskedasticity-Consistent Covariance Matrix Estimator and a Direct Test for Heteroskedasticity." *Econometrica* 48 (4): 817. doi:10.2307/1912934.

Widanarko, B., S. Legg, M. Stevenson, J. Devereux, A. Eng, A. Mannetje, S. Cheng, J. Douwes, L. Ellison-Loschmann, D. McLean, and N. Pearce. 2011. "Prevalence of Musculoskeletal Symptoms in Relation to Gender, Age, and Occupational/Industrial Group." *International Journal of Industrial Ergonomics* 41 (5): 561–572. doi:10.1016/j.ergon.2011.06.002.

Widanarko, B., S. Legg, M. Stevenson, J. Devereux, A. Eng, A. Mannetje, S. Cheng, and N. Pearce. 2012. "Gender Differences in Work-Related Risk Factors Associated with Low Back Symptoms." *Ergonomics* 55 (3): 327–342. doi:10.1080/00140139.2011.642410.

Xu, X., M. Robertson, K. B. Chen, J.-H. Lin, and R. W. McGorry. 2017. "Using the Microsoft Kinect™ to Assess 3-D Shoulder Kinematics during Computer Use." *Applied Ergonomics* 65: 418–423. doi:10.1016/j.apergo.2017.04.004.

Yang, L., L. Zhang, H. Dong, A. Alelaiwi, and A. E. Saddik. 2015. "Evaluating and Improving the Depth Accuracy of Kinect for Windows v2." *IEEE Sensors Journal* 15 (8): 4275–4285. doi:10.1109/JSEN.2015.2416651.