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Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort

P. Madeleine*, T.M.T. Madsen

Laboratory for Ergonomics and Work-related Disorders, Center for Sensory–Motor Interaction (SMI), Department of Health Science and Technology, Aalborg University, Fredrik Bajers Vej 7, Bldg. D-3, DK 9220 Aalborg, Denmark

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ABSTRACT

In this field study, the size and structure of kinematics variability were assessed in relation to experience and discomfort during a deboning task. Eighteen workers divided in groups with low/high experience and with/without neck–shoulder discomfort participated. Standard deviation and coefficient of variation (amount of variability), as well as approximate entropy and sample entropy (complexity) and, correlation dimension (dimensionality) were computed for head–shoulder, shoulder–hip and elbow–hip displacement in the vertical direction. A longer work experience was associated with shorter work cycle duration and decreased amount of variability while complexity increased for the head–shoulder displacement, $P < 0.05$. Shorter work cycle, lower amount of variability and, lower dimensionality for the head–shoulder displacement were found in relation to discomfort, $P < 0.05$. While the amount of variability, complexity and dimensionality increased for the elbow–hip displacement, $P < 0.05$. These findings suggest a functional role of experience via learning effects and discomfort through compensatory mechanisms on the size and structure of motor variability.

1. Introduction

Meat processing involves a considerable amount of manual operations and several studies have demonstrated that workers performing meat processing tasks are at high risk of contracting work-related musculoskeletal disorders (WMSD) (Magnusson et al., 1987; Marklin and Monroe, 1998; Punnett and Wegman, 2004). In the meat processing industry, WMSD most commonly affect the upper extremities including neck and shoulder (Viikari-Juntura et al., 1991; Frost et al., 1998) and the key physical risk factors include exerted force, repetitive movements, lack of recovery, and awkward postures (Sommerich et al., 1993). A general lack of quantitative field studies in meat industry has been expressed (Marklin and Monroe, 1998). Most knowledge about WMSD due to slaughterhouse operations is from experimental studies investigating the effect of cutting force (McGorry et al., 2004) and muscle activity (Grant and Habes, 1997; Madeleine et al., 1999) during specific limb movements, rather than during functional and in vivo work activities (Juul-Kristensen et al., 2002). Quantitative biomechanical analysis can be used to identify motor patterns during work.

Mathiassen et al. (2003) have suggested in a rather unspecific manner that differences in motor patterns and motor control could explain why some workers performing a constrained industrial work task develop WMSD while others, performing the same work task, do not. A recent laboratory study by our group (Madeleine et al., 2008b) demonstrated that the size of cycle-to-cycle variability was larger among experienced butchers compared with novices and suggested that motor patterns change with learning and experience. Moreover, discomfort or pain has also been reported to change the size of motor variability (Parakkat et al., 2007; Madeleine et al., 2008a,b). Variability is a central characteristic of all human movement because of its role in motor learning and control (Latash and Anson, 2006). A few studies have suggested a possible beneficial effect of e.g. varying load and movement pattern for the prevention of WMSD (Kilbom and Persson, 1987; Madeleine et al., 2008a,b). To understand the nature and complexity of the motor variability, a collection of different types of variability measures needs to be considered (Newell and Corcos, 1993; Stergiou, 2004). Thus, a combination of linear parameters along with nonlinear estimators such as approximate entropy or/and correlation dimension has been suggested (Stergiou, 2004).

Linear descriptors such as standard deviation and coefficient of variation are commonly used to characterize the amount of variability in movements (Stergiou, 2004) and to date, variability in ergonomics has only been measured by means of these linear

* Corresponding author. Tel.: +45 99 40 88 33; fax: +45 98 15 40 08.
E-mail address: pm@hst.aau.dk (P. Madeleine).

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descriptors (Moller et al., 2004; Madeleine et al., 2008a,b). However, these approaches do not provide information about the true structure of motor variability (Slifkin and Newell, 1999; Buzzi et al., 2003). Nonlinear analysis derived from chaos theory have contributed the understanding the variations over time of biological signals through e.g. aging and disease (Vaillancourt and Newell, 2002). In this context, approximate and sample entropy as well as correlation dimension can be computed to characterize the complexity and dimensionality of the kinematics signals (Buzzi et al., 2003; Georgoulis et al., 2006). Thus, the idea of combining linear and nonlinear techniques is sound and may expand our knowledge on the amount and structure of variability in ergonomics, and thereby provide valuable information about motor strategies in relation to e.g. experience and discomfort.

This cross-sectional field study focused on motor techniques and variability among slaughterhouse workers performing deboning work. The purpose was to assess motor variability in relation to the subjects' work experience and reported discomfort in the neck–shoulder region using both linear and nonlinear techniques.

2. Methods and materials

2.1. Subjects

18 male slaughterhouse workers, performing deboning work on a daily basis, took part in the study after giving their informed consent to participate. Table 1 presents subjects information. Only right handed workers were included in the study. The study was approved by the local ethics committee (N-20070004MCH) and conducted in conformity with the Declaration of Helsinki.

2.2. Experimental setup

The experimental setup included video recordings of workers manually deboning fore-ends from pigs (approximately 11 kg/fore-end). The operation was not time-paced, consisted in performing multiple cuts to remove three inner bones (shank, humerus and blade) and lasted, under normal conditions, approximately 35–50 s/fore-end. Each worker performed the deboning process approximately 450 times (up to 530 times) per day and received payment accordingly. Each worker was video recorded at their daily workplace while deboning 6 fore-ends to ensure consistent kinematics data. Prior to recordings each worker received instructions related to the experiment. The workers discomfort was assessed using a modified Danish version of the standardised Nordic Questionnaire, i.e. the part about trouble with locomotive organs for analysis of musculoskeletal symptoms (Kuorinka et al., 1987). The questionnaire asked about discomfort in the neck, shoulders, elbows, wrists/hands, upper back, low back, hips and knees in the past week and in the past year. Further, supplementary questions were posed concerning job rotation, sick-leave, possible factors worsening discomfort and presence of symptoms after holidays.

Kinematics data were collected using a digital video camera (Sony, Handycam DCR-DVD205E, Tokyo, Japan) placed on a tripod perpendicular to the workbench and sampled at 25 Hz. Markers were placed on the right side of the head, the right shoulder, the right elbow and the right hip. A reference recording was performed prior to the deboning, in which the workers were placed in an upright anatomical position, so the relative motion of the markers could be calculated for head–shoulder, shoulder–hip and elbow–hip displacement.

Table 1
Subjects information (mean (SD)) with respect to age, height, weight, deboning experience and deboning cycle duration for low (<1 year) and high (>1 year) work experience and with/without discomfort in neck–shoulder region.

	Work experience		Discomfort		Total
	Low	High	With	Without	
N	7	11	6	12	18
Age (yrs)	28.1 (6.4)	40.9 (7.5)	35 (7.5)	36.4 (10.5)	35.9 (9.4)
Height (cm)	175.9 (13.7)	174.6 (6.6)	180.2 (4.1)	172.6 (10.7)	175.1 (9.6)
Weight (kg)	83.3 (14.0)	77.3 (12.0)	80 (11.4)	79.4 (13.9)	79.7 (12.8)
Deboning experience (yrs)	0.4 (0.2)	3.1 (2.0)	3.1 (2.7)	1.5 (1.5)	2.1 (2)
Deboning time (s)	56 (19.5)	39.1 (6.9)	34.8 (5.2)	51.1 (15.6)	45.7 (15.3)

2.3. Data analysis

WINanalyze (vers. 1.3, Mikromak GmbH, Berlin, Germany) was used to digitalize the recorded video sequences. From the recorded data, four representative bouts of approximately 35–50 s for each worker were chosen for analysis. The tracking procedure revealed that most workers rotated the trunk while working, resulting in unreliable horizontal coordinates. Thus, only the vertical coordinates from the data were suitable for analysis. The precision and the accuracy of the kinematics recording in the vertical direction were 0.39 mm and 99.95%.

All further data analysis was conducted in MATLAB (MathWorks, Natick, MA). The digitalized coordinates were low-pass filtered (Butterworth, 2nd order, cut-off frequency 5 Hz). To describe relative work posture, distances in the vertical direction between the four recorded markers were normalised accordingly to the recorded reference position. Data were offset corrected with respect to the upright position (Fig. 1).

2.4. Quantifying motor techniques and variability

The duration of each work cycle (deboning of one fore-end) was calculated as the length of the data series, starting at the first cut and ending when the fore-end left the workbench.

The range of motion (ROM) for the vertical displacement of the head–shoulder, shoulder–hip and elbow–hip relative motion was calculated. The mean and the 10th, 50th and 90th percentile of the displacement were also computed.

To quantify the size of variability, standard deviation (SD) and coefficient of variation (CV) were calculated for the vertical displacement of the head–shoulder, shoulder–hip and elbow–hip relative motion. A set of different nonlinear methods was used for the vertical displacement of the head–shoulder, shoulder–hip and elbow–hip relative motion to estimate:

(i) the complexity, i.e. approximate entropy (ApEn) and sample entropy (SaEn) and
(ii) the dimensionality, i.e. correlation dimension (CD) of the kinematics time series (see Appendix).

ApEn and SaEn both quantify the probability that two sequences that are similar for m observations remain close on the next incremental comparison $m+1$ (Pincus, 1991; Richman and Moorman, 2000). The output is a single nonnegative number, where larger values indicate more complex structure in the data (Richman and Moorman, 2000; Harbourne and Stergiou, 2003). The embedding dimension, m, and the tolerance distance, r, were, in the present study, chosen to $m=2$ and $r=0.2\times\mathrm{SD}$, on the basis of human movement studies using ApEn and SaEn (Vaillancourt and Newell, 2000; Stergiou, 2004). The CD is an

Fig. 1. Example showing how the displacements in vertical direction were computed for head–shoulder, shoulder–hip and elbow–hip.

approximation of how data points of a dynamical system are organized within a state space (Kuusela et al., 2002; Harbourne and Stergiou, 2003). The CD is a static approximation of the fractal dimension or dimensionality of a dynamic system and aims at establishing a stable value. CD was estimated using a Gaussian kernel algorithm with the embedding dimension m, embedding lag τ and the number of bins of inter-point distances respectively set to 10, 1 and 200 (Small, 2005).

2.5. Statistical analyses

To assess the association with work experience, subjects were divided into either a low or a high experience group (Table 1). The low/high experience group consisted of workers with less/more than one year experience with deboning in accordance with previous studies (Hakkanen et al., 2001; Parakkat et al., 2007). Further, to analyze the relation between discomfort and kinematics data, subjects were divided into workers with and without discomfort in the neck–shoulder region (Table 1). The dichotomy was made on the basis of discomfort in the neck–shoulder region within the past week.

Multivariate analysis of variance (MANOVA) in SPSS version 15.0 (Chicago, Il, USA) was used with the following factors (i) work experience and (ii) discomfort in neck–shoulder within the past week for the dependent variables: mean, 10th, 50th and 90th percentile, ROM, SD, CV, ApEn, SaEn and, CD. Mean (SD) are reported. The level of significance was set at $P < 0.05$.

3. Results

3.1. Motor changes in relation to work experience

The work cycle duration was significantly longer ($F = 18.06$; $P < 0.001$) for workers with low experience compared with workers with high experience (Table 1). For the work cycle duration, there was also a significant interaction between discomfort and work experience ($F = 5.0$, $P = 0.028$). The duration was shorter in presence of discomfort compared with no discomfort for workers with low experience (respectively, 39.3 (3.3) s vs. 62.7 (19.3) s, $P < 0.05$) and decreased from low to high experience in presence of discomfort (respectively, 39.3 (3.3) s vs. 32.5 (4.5) s, $P < 0.05$).

The relations between work experience and the parameters describing movement amplitude are reported in Fig. 2. For the head–shoulder position, the ROM ($F = 5.7$; $P = 0.02$) and 10th percentile ($F = 4.5$; $P = 0.038$) were significantly higher for workers with low experience compared with workers with high experience, respectively for ROM, 20 (4.8) cm vs. 17.1 (4.6) cm.

Table 2 presents the SD and CV for workers with low and high experiences. The workers with low experience had significantly larger SD for the head–shoulder displacement compared with the workers with high experience ($F = 7.6$; $P = 0.008$).

Fig. 3 presents the computed nonlinear parameters in relation to work experience. ApEn for head–shoulder displacement was smaller for the workers with low experience compared with workers with high experience ($F = 4.5$; $P = 0.037$).

3.2. Motor changes in relation to discomfort

The workers with neck–shoulder discomfort had shorter cycle duration ($F = 9.3$; $P = 0.003$) compared with workers without discomfort (Table 1).

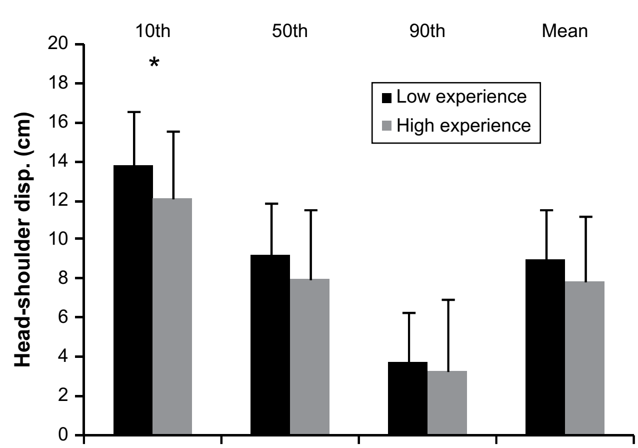

Fig. 2. 10th, 50th, 90th percentile and mean head–shoulder displacement (cm) in the vertical direction. Group mean values with SD are shown for workers with low experience (<1 year, $N = 7$) and high experience (>1 year, $N = 11$). *Indicates statistical differences ($P < 0.05$).

Table 2
Mean (SD) for standard deviation (SD) and coefficient of variation (CV) for workers with low (<1 year) and high (>1 year) experience. *Significant group differences ($P < 0.05$).

		Experience	
		Low	High
Head–shoulder	SD (cm)	3.9 (0.8)*	3.4 (0.8)*
	CV	−0.5 (0.2)	−0.5 (0.4)
Shoulder–hip	SD (cm)	3.4 (0.7)	3.5 (0.9)
	CV	−0.2 (1.6)	−0.2 (3.1)
Elbow–hip	SD (cm)	6.6 (1.3)	6.5 (1.6)
	CV	0.9 (0.6)	2.7 (8.7)

The relations between discomfort and the parameters describing movement amplitude are reported in Fig. 4. The workers with neck–shoulder discomfort had larger mean ($F = 5.9$; $P = 0.017$), 50th ($F = 7.1$; $P = 0.01$) and 90th percentile values ($F = 4.3$; $P = 0.041$) compared with workers without discomfort.

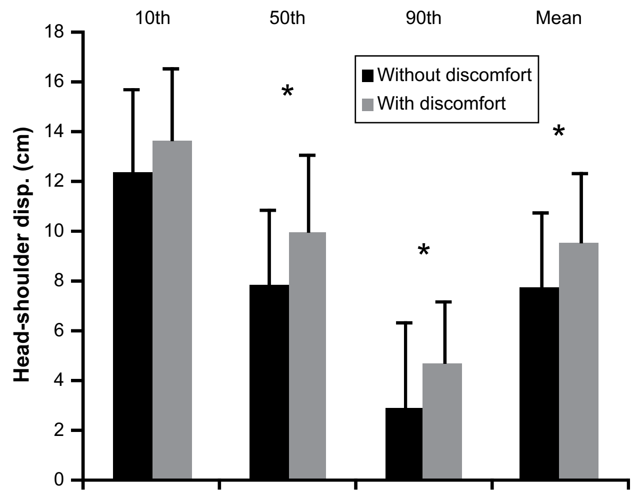

Fig. 4. 10th, 50th, 90th percentile and, mean head–shoulder displacement (cm) in the vertical direction. Group mean values with SD are shown for workers without ($N = 12$) and with ($N = 6$) neck–shoulder discomfort. *Indicates statistical differences ($P < 0.05$).

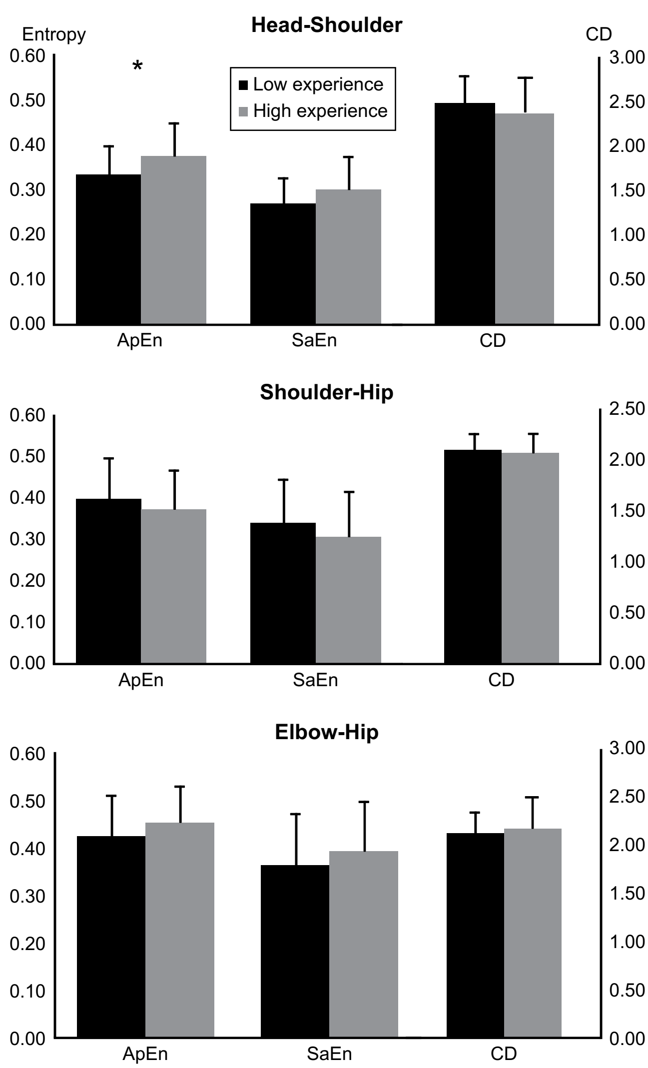

Fig. 3. Approximate entropy (ApEn), sample entropy (SaEn) and correlation dimension (CD) for head–shoulder, shoulder–hip and elbow–hip displacements in the vertical direction. Group mean values with SD are shown for workers with low experience (<1 year, $N = 7$) and high experience (>1 year, $N = 11$). *Indicates statistical differences ($P < 0.05$).

Table 3 presents the SD and CV for workers with and without discomfort. CV was lower for workers with neck–shoulder discomfort compared with workers without discomfort for the head–shoulder displacement ($F = 4.9$; $P = 0.03$) and the shoulder–hip displacement ($F = 3.9$; $P = 0.05$), while it was opposite for the SD of the elbow–hip displacement ($F = 6.9$; $P = 0.011$).

Fig. 5 presents the computed nonlinear parameters in relation to discomfort. CD for the head–shoulder displacement was significantly smaller for workers with neck–shoulder discomfort compared with workers without discomfort ($F = 3.8$; $P = 0.048$). Further, ApEn, SaEn and CD were higher for workers with neck–shoulder discomfort compared with workers without discomfort for the elbow–hip displacement (respectively, $F = 4.9$; $P = 0.03$, $F = 7.8$, $P = 0.007$; $F = 8.0$, $P = 0.006$).

4. Discussion

In this study, both linear and nonlinear approaches were used for the first time to quantify and characterize changes in motor variability of kinematics data during a deboning process. A longer work experience was associated with shorter work cycle duration and changes of the vertical displacement of the head and shoulder positions e.g. decrease range of motion, 10th percentile and amount of variability (standard deviation) while complexity (approximate entropy) increased. In presence of discomfort in the neck–shoulder region, shorter work cycle, increased displacement of the head–shoulder vertical positions, lower amount of

Table 3
Mean (SD) for standard deviation (SD) and coefficient of variation (CV) for workers with and without neck–shoulder discomfort reported within last week. *Significant group differences ($P < 0.05$).

		Neck–shoulder discomfort	
		Without	With
Head–shoulder	SD (cm)	3.6 (0.9)	3.5 (0.8)
	CV	−0.6 (0.4)*	−0.4 (0.1)*
Shoulder–hip	SD (cm)	3.5 (0.9)	3.5 (0.5)
	CV	−0.3 (2.1)*	0.1 (3.3)*
Elbow–hip	SD (cm)	6.3 (1.4)*	7.2 (1.2)*
	CV	2.0 (6.7)	0.8 (0.2)

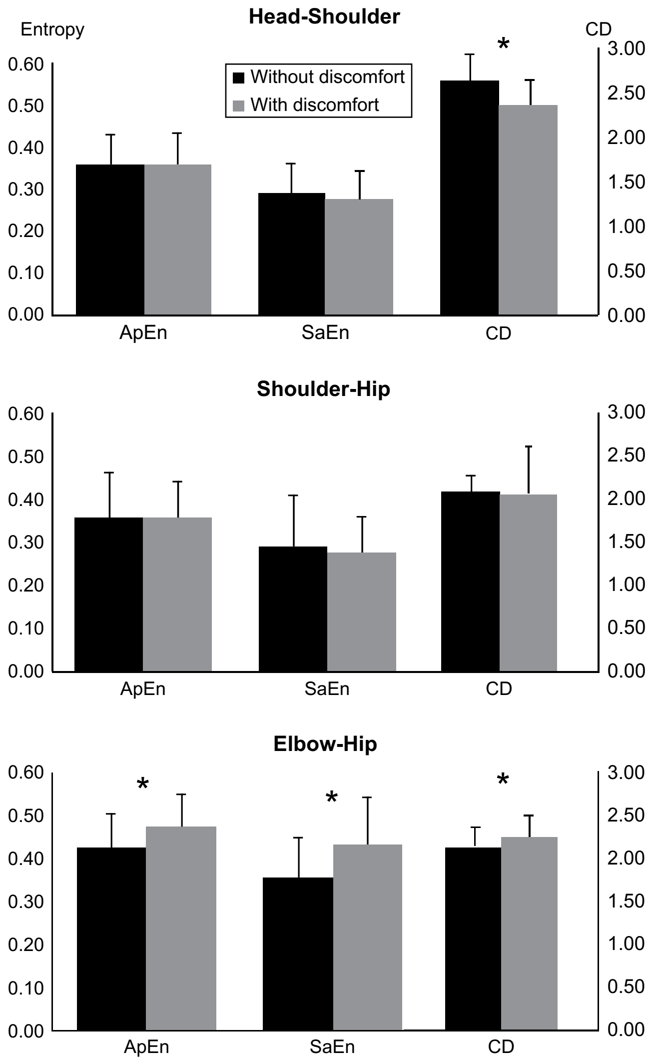

Fig. 5. Approximate entropy (ApEn), sample entropy (SaEn) and correlation dimension (CD) for head–shoulder, shoulder–hip and elbow–hip displacements in the vertical direction. Group mean values with SD are shown for workers without ($N = 12$) and with ($N = 6$) neck–shoulder discomfort. *Indicates statistical differences ($P < 0.05$).

variability (coefficient of variation) and, lower dimensionality (correlation dimension) were found for the head–shoulder vertical displacement, in contrast to a greater amount of variability (standard deviation), complexity (approximate and sample entropy) and dimensionality (correlation dimension) for the vertical displacement of elbow–hip.

4.1. Methodological consideration

The present field study was conducted in a slaughterhouse. Thus, factors like work organization (e.g. piece-rate), incentive system and workplace physical environment (e.g. lightning condition, ambient temperature, humidity, meat temperature and, tools quality) were taken into consideration. On the other hand, the work task did not enable a 2D kinematics analysis as expected, and the movements were only assessed in the vertical direction as also reported in another study (Piedrahita et al., 2008). Moreover, age differences between workers with low and high experiences can be considered as a cofounder (Madeleine et al., 2003a). The study population was small but sufficient to generate new information related to motor variability in ergonomics.

Workers were divided in low/high experience groups if they had been performing the deboning task for less/more than one year as it has also been done in previous studies (Hakkanen et al., 2001; Parakkat et al., 2007). With respect to discomfort, we decided to limit ourselves to the neck–shoulder region due to the high prevalence of neck–shoulder pain in meat processing industry (Viikari-Juntura et al., 1991; Frost et al., 1998). Among the six workers with neck–shoulder discomfort, five reported discomfort within the past week in both the neck and shoulders and one only reported discomfort in shoulders. Moreover, four of these six workers reported discomfort in hand/wrist, three in the low back, two in the knee and one in the elbow and hip in the past week. Three out of six had been on sick-leave in the past year. Finally, two of them reported that discomfort did not disappear after holidays. The differences reported in relation to experience and discomfort were small but can be of importance when considering exposure over hours, days, months and years. The findings related to variability obtained here, are inherent to both flexibility in motor control and consistency in production (Moller et al., 2004; Madeleine et al., 2008b).

Further, experience and discomfort are cofounded factors. Moreover, the cause–effect relationship between experience/discomfort and motor variability cannot be inferred from the present cross-sectional design and emphasizes the need for longitudinal studies. Finally, regardless of its limitations, the present study provides important new and complementary findings to previous studies (Mathiassen et al., 2003; Moller et al., 2004; Mathiassen, 2006; Madeleine et al., 2008a,b) with respect to the relation between experience/discomfort and the amount and structure of motor variability during repetitive work.

4.2. Motor changes in relation to work experience

In the present study, workers with low experience (less than one year) had longer work cycle durations than the more experienced workers. This finding is in line with previous reports on cycle durations among butchers participating in a 6-month prospective study in laboratory conditions (Madeleine et al., 2003a,b) and in a field study (Dempsey and McGorry, 2004). To optimize the performance of the deboning task, motor learning effect is likely to take place based on the integration and adaptation of movement building blocks located in the central nervous system (Kargo and Nitz, 2003). This was also corroborated by the decreased head and shoulder position range of motion and amount of variability found among workers with more than one year experience compared with less experienced ones. Concomitantly to that, the structure of the variability increased pointing towards more complex movement.

In a prior laboratory study, increased amount of movement variability during a simulated work task has been reported for butchers with increasing experience (from 0 to 6 months experience) and for experienced butchers compared with novices (Madeleine et al., 2008b). An increasing size of movement variability with increasing skill level could be attributed to the specific task constraints or specific nature of the task dynamics (Broderick and Newell, 1999). Moreover, one should keep in mind that the simulated work task in Madeleine et al. (2008b) was not a true copy of the butchers habitual work. Thus, the extend of motor transfer occurring via e.g. adaptation process from the usual to the simulated work task is unknown and may partly account for differences in motor variability (Madeleine et al., 2008b). In this study, the greater amount of variability and the decreased complexity among workers with low experience might also be explained by the fact that deboning is a high demanding task in terms of productivity and precision. Thus, a worker with low experience might want to ensure correct cuts, resulting in frequent bending of his head leading to increase range of motion to achieve a better work precision. Our results are also in line with a biomechanical study investigating spinal loads and reporting lower variability during a lifting task among less experienced subjects (Granata et al., 1999). The increased amount of variability together with a decreased complexity of the kinematics in the vertical direction for workers with less than one year experience reflects flexibility in motor control as well as consistency in production. Finally, the present results suggest that a deboning experience of approximately 5 months (Table 1) is not sufficient to acquire a fully tuned motor strategy.

4.3. Motor changes in relation to discomfort

Discomfort in the neck–shoulder region in the past week was associated with shorter work cycle duration. In prior laboratory studies, the duration of cycle time and its amount of variability have been found to increase in neck–shoulder pain condition compared with pain-free condition (Madeleine et al., 1999, 2008a,b). Discrepancies among the two investigated tasks may again account for those differences.

In terms of movement, neck–shoulder discomfort was associated with an increase of the vertical distance for the head–shoulder. This indicated that workers with discomfort operated in a posture where the head was either less flexed or shoulders were less elevated compared with the workers not reporting discomfort. Discomfort is also reported to influence the spinal load pattern during a lifting task (Parakkat et al., 2007). Further, muscle pain influences the neck and shoulder posture at work (Madeleine et al., 1999, 2008a, 2003b; Szeto et al., 2002; Côté et al., 2005) even though some studies have reported no changes during work with lower physical demand (Birch et al., 2001; Arvidsson et al., 2008). We have indeed shown in laboratory conditions, that acute, sub-chronic or chronic neck–shoulder pain are accompanied by neuromuscular adaptations that can explain the transition from acute to chronic states (Madeleine et al., 2003b, 2008a). At sub-chronic or chronic pain stages, a decrease in the magnitude of arm and trunk motor variability has been observed (Madeleine et al., 2008a,b). Our results are consistent with the changes in kinematics variability induced by sub-chronic or chronic pain as the amount of variability and the dimensionality of the head–shoulder kinematics data was decreased among workers with neck–shoulder discomfort compared with workers without discomfort. A decrease in dimensionality is reported to be associated with a decrease in the amount of degree of freedom used (Harbourne and Stergiou, 2003). Then, our results suggest that discomfort is associated with a more stereotypic working strategy in the unpleasant body region. Moreover, compensatory mechanisms in remote regions are likely to occur as greater amount of variability, complexity and dimensionality for the elbow–hip vertical positions were also found among workers with discomfort. Thus, the present study showed that the size and structure of movement variability are changed in relation to discomfort in the reported region and also in remote locations.

4.4. Can motor variability prevent the development of WMSD?

Motor control variability in the traditional sense focuses on variation in movement sequences and their outcome. Increased variability relative to some a priori standard should then reflect a problem of control or some sensory-motor mismatch (Newell and Corcos, 1993). With respect to a task-specific performance variable, motor variability has been addressed as "good" when the outcome variable was not affected or "bad" when it was changed (Latash and Anson, 2006).

The present results underlined the difficulty in defining motor variability as either "good" or "bad", especially when taking in consideration size and structure of motor variability. For the workers with discomfort, the larger amount of variability, complexity and dimensionality observed in the elbow–hip positions could be a secondary effect of the changes that took place for the head and shoulder position, i.e. decrease in amount and dimensionality of variability in relation to neck–shoulder discomfort. Then, the observed increased variability in elbow–hip could be interpreted as a negative trend. On the other hand, the greater variability in head–shoulder seen among the workers without complaint could be interpreted as a positive trait as it may avoid discomfort in the neck–shoulder region.

Discomfort may reflect a step towards pain (Madeleine et al., 1998; Parakkat et al., 2007). Kilbom and Persson (1987) have reported that workers using a more dynamic pattern of movements had a lower risk of developing WMSD. In line with this, the size of motor variability is found modulated by neck–shoulder pain (Madeleine et al., 2008a,b). Then a higher amount of variability and dimensionality among workers without neck–shoulder discomfort may prevent WMSD development as suggested earlier (Kilbom and Persson, 1987; Mathiassen, 2006; Moseley and Hodges, 2006; Madeleine et al., 2008a,b).

5. Conclusion

This cross-sectional field study provides new quantitative kinematics descriptions (vertical direction) of a deboning task. Besides using traditional kinematics variables and linear techniques for estimating the amount of motor variability, the paper introduced nonlinear approaches for assessing the structure of variability in ergonomics for the first time. Workers with high experience (more than 1 year) in fore-end deboning were characterized by shorter duration of the work cycle, smaller range of motion, 10th percentile and amount of variability and higher complexity compared with workers with low experience. This most likely indicates that 5-month experience is insufficient to acquire a stable motor strategy. Discomfort in the neck–shoulder region was associated with shorter work cycle, increased amplitude, lower amount of variability and dimensionality for the head–shoulder displacement while the amount of variability, the complexity and the dimensionality increased for the elbow–hip displacement. This can probably be explained by compensatory mechanisms in relation to neck–shoulder discomfort. Finally, longitudinal studies investigating the role amount and structure of variability in relation to e.g. WMSD are needed within ergonomics.

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Appendix

1. Approximate entropy (ApEn)

ApEn quantifies the complexity or structure of variability of a time series $x(i)$ (Pincus, 1991; Pincus and Goldberger, 1994). ApEn is derived from the correlation function $C(r)$ (Grassberger and

Procaccia, 1983). First, the time series $x(i)$ with $i = 1,\ldots,N$ is divided into $N - m + 1$ vectors $u(i)$ of the state space:

$$u(i) = [x(i), x(i+\tau), x(i+2\tau), \ldots, x(i+(m-1)\tau)]$$

where m is the embedding dimension and τ the time lag (set to 1). Then, the distance d is calculated as the maximal distance d between each vector in the state space:

$$d[u(i), u(j)] = \max(|u(i+k) - u(j+k)|), \text{ with } 1 \le j \le N - m + 1 \text{ and } 0 \le k \le m - 1$$

C_i^m is the number of vectors $u(j)$ within the distance r from the template vector $u(i)$ computed as:

$$C_i^m(r) = (N - m + 1)^{-1} \sum_{i=1}^{N-m+1} H(r - |d(u(i), u(j))|)$$

with $H()$ being the Heaviside step function where H is 1 if $(r - |d(u(i), u(j))|) \ge 0$ and 0 otherwise. Then, $\Phi^m(r)$ representing the average of natural logarithm of C_i^m is computed as:

$$\Phi^m(r) = (N - m + 1)^{-1} \sum_{i=1}^{N-m+1} \ln C_i^m(r)$$

Finally, the ApEn is expressed as the difference between the logarithmic probability that vectors which are close for m points are also close if lengthened to $m + 1$ points.

$$\mathrm{ApEn}(m, r, N) = \Phi^m(r) - \Phi^{m+1}(r)$$

ApEn depends on the embedding dimension m, the criterion for similarity r and the number of data points N. In general, m is set to 1 or 2 to insure good statistical validity, r is set to 10% or 20% of the standard deviation of the time series while N should exceed 800 points (Pincus, 1991; Vaillancourt and Newell, 2000; Kuusela et al., 2002; Stergiou, 2004).

2. Sample entropy (SaEn)

SaEn quantifies also the complexity of a time series but its computation differs from ApEn as self-matches are now excluded, the first $N - m$ vectors are considered and the conditional probability is not estimated in a template manner (Richman and Moorman, 2000). In practice, it means that when the distance d between $u(i)$ and $u(j)$ is computed, i is never equal to j.

$$d[u(i), u(j)] = \max(|u(i+k) - u(j+k)|), \text{ with } 1 \le j \le N - m \text{ and } i \ne j$$

Now, $\Phi'^m(r)$ representing the average of natural logarithm of the probability of matches $C_i'^m$ is computed as:

$$\Phi'^m(r) = (N - m)^{-1} \sum_{i=1}^{N-m} C_i'^m(r)$$

Finally, SaEn representing the negative logarithm of the relationship between the probability that two sequences coincide for $m + 1$ and m points can be computed as:

$$\mathrm{SaEn}(m, r, N) = -\ln\left(\frac{\Phi'^{m+1}(r)}{\Phi'^m(r)}\right)$$

SaEn also depends on the embedding dimension m, the criterion for similarity r and the number of data points N. m is in general also set to 1 or 2 to enable a more consistent estimation (Lake et al., 2002). SaEn decreases monotonically as r increases and does not depend in theory on N (Richman and Moorman, 2000; Kuusela et al., 2002).

3. Correlation dimension (CD)

The correlation dimension (CD) assesses the dimensionality of a dynamic system, i.e. an approximation of how data points are organized within a space state. In order to estimate CD, the correlation function $C(r)$ introduced by Grassberger and Procaccia (1983) has to be computed. A Gaussian kernel algorithm was used to compute the correlation function due to its relative robustness to noise (Diks, 1996; Small, 2005). Vectors $u(i)$ of the space state are constructed as explained in part 1 of the appendix. Then, the number of vectors within the distance r from a given vector is computed as:

$$C(r) = \lim_{N \to \infty} \frac{1}{N^2} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ i \ne j}}^{N} H(r - |x(i) - x(j)|)$$

with $H()$ being again the Heaviside step function where H is 1 for positive values and 0 otherwise. $C(r)$ has been found to follow a power law for a limited range of r, $C(r) \sim \text{const } r^{\mathrm{CD}}$. Then, CD is determined as limit value:

$$\mathrm{CD}(m, r) = \lim_{r \to 0} \frac{\ln(C(r))}{\ln(r)}$$

In practice, CD is estimated as the slope of the regression line in a linear portion of the log–log plot. CD depends on the embedding dimension m, the time delay τ and the number of bins of interpoints distance (Small, 2005). Moreover, CD is sensitive to measurement noise and nonstationarities of the signal (Kuusela et al., 2002).

References

Arvidsson, I., Hansson, G.A., Mathiassen, S.E., Skerfving, S., 2008. Neck postures in air traffic controllers with and without neck/shoulder disorders. Appl. Ergon. 39, 255–260.

Birch, L., Arendt-Nielsen, L., Graven-Nielsen, T., Christensen, H., 2001. An investigation of how acute muscle pain modulates performance during computer work with digitizer and puck. Appl. Ergon. 32, 281–286.

Broderick, M.P., Newell, K.M., 1999. Coordination patterns in ball bouncing as a function of skill. J. Mot. Behav. 31, 165–188.

Buzzi, U.H., Stergiou, N., Kurz, M.J., Hageman, P.A., Heidel, J., 2003. Nonlinear dynamics indicates aging affects variability during gait. Clin. Biomech. 18, 435–443.

Côté, J.N., Raymond, D., Mathieu, P.A., Feldman, A.G., Levin, M.F., 2005. Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. Clin. Biomech. 20, 581–590.

Dempsey, P.G., McGorry, R.W., 2004. Investigation of a pork shoulder deboning operation. J. Occup. Environ. Hyg. 1, 167–172.

Diks, C., 1996. Estimating invariants of noisy attractors. Phys. Rev. E 53, R4263–R4266.

Frost, P., Andersen, J.H., Nielsen, V.K., 1998. Occurrence of carpal tunnel syndrome among slaughterhouse workers. Scand. J. Work Environ. Health 24, 285–292.

Georgoulis, A.D., Moraiti, C., Ristanis, S., Stergiou, N., 2006. A novel approach to measure variability in the anterior cruciate ligament deficient knee during walking: the use of the approximate entropy in orthopaedics. J. Clin. Monit. Comput. 20, 11–18.

Granata, K.P., Marras, W.S., Davis, K.G., 1999. Variation in spinal load and trunk dynamics during repeated lifting exertions. Clin. Biomech. 14, 367–375.

Grant, K.A., Habes, D.J., 1997. An electromyographic study of strength and upper extremity muscle activity in simulated meat cutting tasks. Appl. Ergon. 28, 129–137.

Grassberger, P., Procaccia, I., 1983. Characterization of strange attractors. Phys. Rev. Lett. 50, 346–349.

Hakkanen, M., Viikari-Juntura, E., Martikainen, R., 2001. Job experience, work load, and risk of musculoskeletal disorders. Occup. Environ. Med. 58, 129–135.

Harbourne, R.T., Stergiou, N., 2003. Nonlinear analysis of the development of sitting postural control. Dev. Psychobiol. 42, 368–377.

Juul-Kristensen, B., Fallentin, N., Hansson, G.-Å., Madeleine, P., Andersen, J., Ekdal, C., 2002. Force demands during manual and mechanical deboning of poultry estimated by electromyography, force transducer, observation method and electrogoniometer. Int. J. Ind. Ergon. 29, 107–115.

Kargo, W.J., Nitz, D.A., 2003. Early skill learning is expressed through selection and tuning of cortically represented muscle synergies. J. Neurosci. 23, 11255–11269.

Kilbom, A., Persson, J., 1987. Work technique and its consequences for musculoskeletal disorders. Ergonomics 30, 273–279.

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Bieringsorensen, F., Andersson, G., Jorgensen, K., 1987. Standardized Nordic questionnaires for the analysis of musculoskeletal symptoms. Appl. Ergon. 18, 233–237.

Kuusela, T.A., Jartti, T.T., Tahvanainen, K.U.O., Kaila, T.J., 2002. Nonlinear methods of biosignal analysis in assessing terbutaline-induced heart rate and blood pressure changes. Am. J. Physiol. Heart Circ. Physiol. 282, 773–783.

Lake, D.E., Richman, J.S., Griffin, M.P., Moorman, J.R., 2002. Sample entropy analysis of neonatal heart rate variability. Am. J. Physiol. Regul. Integr. Comp. Physiol. 283, R789–R797.

Latash, M.L., Anson, J.G., 2006. Synergies in health and disease: relations to adaptive changes in motor coordination. Phys. Ther. 86, 1151–1160.

Madeleine, P., Lundager, B., Voigt, M., Arendt-Nielsen, L., 1999. Shoulder muscle coordination during chronic and acute experimental neck–shoulder pain. An occupational study. Eur. J. Appl. Physiol. 79, 127–140.

Madeleine, P., Lundager, B., Voigt, M., Arendt-Nielsen, L., 2003a. Standardized low-load repetitive work: evidence of different motor control strategies between experienced workers and a reference group. Appl. Ergon. 34, 533–542.

Madeleine, P., Lundager, B., Voigt, M., Arendt-Nielsen, L., 2003b. The effects of neck–shoulder pain development on sensory–motor interaction among female workers in poultry and fish industries. A prospective study. Int. Arch. Occup. Environ. Health 76, 39–49.

Madeleine, P., Mathiassen, S.E., Arendt-Nielsen, L., 2008a. Changes in the amount of motor variability associated with experimental and chronic neck–shoulder pain during a standardised repetitive arm movement. Exp. Brain Res. 185, 689–698.

Madeleine, P., Voigt, M., Mathiassen, S.E., 2008b. The size of cycle-to-cycle variability in biomechanical exposure among butchers performing a standardised cutting task. Ergonomics 51, 1078–1095.

Madeleine, P., Voigt, M., Arendt-Nielsen, L., 1998. Subjective, physiological and biomechanical responses to prolonged manual work performed standing on hard and soft surfaces. Eur. J. Appl. Physiol. 77, 1–9.

Magnusson, M., Ortengren, R., Andersson, G.B.J., Petersen, I., Sabel, B., 1987. An ergonomic study of work methods and physical disorders among professional butchers. Appl. Ergon. 18, 43–50.

Marklin, R.W., Monroe, J.F., 1998. Quantitative biomechanical analysis of wrist motion in bone-trimming jobs in the meat packing industry. Ergonomics 41, 227–237.

Mathiassen, S.E., 2006. Diversity and variation in biomechanical exposure: what is it, and why would we like to know? Appl. Ergon. 37, 419–427.

Mathiassen, S.E., Moller, T., Forsman, M., 2003. Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. Ergonomics 46, 800–824.

McGorry, R.W., Dempsey, P.G., O'Brien, N.V., 2004. The effect of workstation and task variables on forces applied during simulated meat cutting. Ergonomics 47, 1640–1656.

Moller, T., Mathiassen, S.E., Franzon, H., Kihlberg, S., 2004. Job enlargement and mechanical exposure variability in cyclic assembly work. Ergonomics 47, 19–40.

Moseley, G.L., Hodges, P.W., 2006. Reduced variability of postural strategy prevents normalization of motor changes induced by back pain: a risk factor for chronic trouble? Behav. Neurosci. 120, 474–476.

Newell, K.M., Corcos, D.M., 1993. Variability and Motor Control. Human Kinetics, Champaign, IL.

Parakkat, J., Yang, G., Chany, A.M., Burr, D., Marras, W.S., 2007. The influence of lift frequency, lift duration and work experience on discomfort reporting. Ergonomics 50, 396–409.

Piedrahita, H., Oksa, J., Malm, C., Sormunen, E., Rintamäki, H., 2008. Effects of cooling and clothing on vertical trajectories of the upper arm and muscle functions during repetitive light work. Eur. J. Appl. Physiol. 104, 183–191.

Pincus, S.M., 1991. Approximate entropy as a measure of system-complexity. Proc. Natl. Acad. Sci. USA 88, 2297–2301.

Pincus, S.M., Goldberger, A.L., 1994. Physiological time-series analysis – what does regularity quantify. Am. J. Physiol. 266, 1643–1656.

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

Richman, J.S., Moorman, J.R., 2000. Physiological time-series analysis using approximate entropy and sample entropy. Am. J. Physiol. Heart Circ. Physiol. 278, 2039–2049.

Slifkin, A.B., Newell, K.M., 1999. Noise, information transmission, and force variability. J. Exp. Psychol. Hum. Percept. Perform. 25, 837–851.

Small, M., 2005. Applied Nonlinear Time Series Analysis: Applications in Physics, Physiology and Finance. World Scientific Publishing, Singapore.

Sommerich, C.M., Mc Glothin, J., Marras, W.S., 1993. Occupational risk factors associated with soft tissue disorders of the shoulder: a review of recent investigations in the literature. Ergonomics 36, 697–717.

Stergiou, N., 2004. Innovative Analysis of Human Movement. Human Kinetics, Champaign, IL.

Szeto, G.P.Y., Straker, L., Raine, S., 2002. A field comparison of neck and shoulder postures in symptomatic and asymptomatic office workers. Appl. Ergon. 33, 75–84.

Vaillancourt, D.E., Newell, K.M., 2002. Changing complexity in human behavior and physiology through aging and disease. Neurobiol. Aging 23, 1–11.

Vaillancourt, D.E., Newell, K.M., 2000. The dynamics of resting and postural tremor in Parkinson's disease. Clin. Neurophysiol. 111, 2046–2056.

Viikari-Juntura, E., Kurppa, K., Kuosma, E., Huuskonen, M., Kuorinka, I., Ketola, R., Konni, U., 1991. Prevalence of epicondylitis and elbow pain in the meat-processing industry. Scand. J. Work Environ. Health 17, 38–45.