Cutting force and EMG recording for ergonomics assessment of meat cutting tasks : influence of the workbench height and the cutting direction on muscle activation levels

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DRAFT : CUTTING FORCE AND EMG RECORDINGS FOR ERGONOMICS ASSESSMENT OF MEAT CUTTING TASKS: INFLUENCE OF THE WORKBENCH HEIGHT AND THE CUTTING DIRECTION ON MUSCLE ACTIVATION LEVELS

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ABSTRACT

Repetitive arm movement and force exertion are common in meat cutting tasks and often lead to musculoskeletal disorders. In this study, the effects of the workbench height and the cutting direction on the levels of muscular activation of the upper extremity during meat cutting tasks were investigated. Seven subjects performed 4 trials of 20s each at the 4 different heights (0 cm, −10 cm, −20 cm and −30 cm below the elbow height), alternating two cutting directions. Activation levels of upper extremity muscles (biceps brachii, triceps long head, deltoideus anterior, deltoideus medialis and upper trapezius) and cutting forces were recorded synchronously. Then the trends of the normalized activations with regard to the workplace design parameters (table height and cutting direction) were computed. Results showed that the optimal configuration is a partially related to the task, whereas motor control strategies have also an influence on it. The present results provide new key information about the effects of workbench heights during a repetitive meat cutting task and a complete assessment protocol to analyse workstation design parameters influence on muscles activation levels.

KEYWORDS

Trend, Spatial activation, Slaughterhouse, Musculoskeletal disorders, Task assessment

INTRODUCTION

Meat cutting tasks performed in slaughterhouses are highly related to the development of musculoskeletal disorders (MSD) [1]. This can be explained by the presence of many of the highly-reported physical risk factors like repetitive arm movements, strenuous work, relative short work cycle duration, insufficient rest, static posture and cold temperature [2,3]. The most common location for these disorders among butchers is the neck-shoulder region. The etiology of MSD is poorly understood, therefore studies assessing the biomechanics of cutting tasks in greater detail have potential to explain the complex inter-relations between internal (sleep propensity, level of performance,...) and external (workstation design, physical and social environment) risk factors [4, 5]. The main part of the literature analysing the cutting force is based on relative simple force assessment as only the resulting force was measured [6, 7]. Indeed assessing the resulting cutting forces in relation with representative synergistic muscle activations exerted by the worker during the task is necessary. McGorry [8] has designed a knife instrumented with strain gauges to record reactive forces and grip moments. This knife led to a more precise estimation of the intensity level of the task. However, no knife measuring force in 3D has to our knowledge been used in combination with electromyographic measurement. Such an experimental design has the potential to estimate the muscle activation levels during a cutting task and to assess the influence of workplace design parameters on those activations.

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The present study aims at providing data for a complete analysis of the cutting force and the activation of representative synergistic muscles in relation with the workbench height and the cutting direction. The study also aimed at analysing the trend of relative activations (normalized to the cutting task force and the cutting task duration) to define the best workstation configuration.

First are presented the experimental setup and the methods used to define the activation trends with regard to the workplace design parameters (table height and cutting direction). Then complete results of a study on seven subjects are analysed and discussed. At last a conclusion provides information on the implication of such study in the design of workplaces.

EXPERIMENTAL SETUP

Experimental protocol

Figure 1 shows an overview of the experimental setup. Seven subjects (age : 29 ± 5 years old, height: 182 ± 8 cm, weight: 77 ± 16 kg) participated to the experimentation. Each subject was standing in front a workbench that represents the workspace. The table height was set up to be at the same height as the elbow for a neutral position of the arm (recommended height for light work [9]). Two main directions of cutting were designed on the work plane, i.e. arm flexion and a combination of arm internal rotation and abduction. Figures 1 and 2 illustrate the directions of cutting with respect to the surface of the workbench. The subject was asked to perform cutting tasks in these two directions for 20 seconds corresponding to approximately 10 cycles in line with [6]. The subject alternated both directions without any speed constraint. The subject repeated this motion at 4 different heights. The first height (reference height) corresponds to the elbow height for a neutral position of the arm (0 *cm*). The other heights are respectively -10 *cm*, -20 *cm* and -30 *cm* below this reference position. The 4 trials were realized in a randomized order to prevent any cross-over effect.

To obtain realistic cutting forces, a standard oscilloscope was providing a visual feedback to the subject. Two grooves were designed on the workplane to ensure that the cutting direction was constant. This setup ensured to obtain a resulting cutting force of 30-50 N in average. This value was close to the one observed in previous studies about cutting tasks [7, 10].

Instrumented knife

The knife was based on the instrumentation of a 3D force sensor (FS6, AMTI, Watertown, MA, USA). The applied forces to the force transducer were recorded as sketched in figure 3. The directions of force exertion were denoted as the "x-direction" for Fx, the "y-direction" for Fy and the "z-direction" for Fz (3). Force signals were low-pass filtered (10.5 Hz) and amplified 2000 times. The signals were A/D converted and sampled at 60 Hz (12 bits A/D converter, Nidaq 6024, National Instruments, Austin, TX, USA) and recorded through a custom made program in LabView 8.2 (National Instruments, Austin, TX,USA). A visual feedback on cutting force was provided to the experimenter with an oscilloscope.

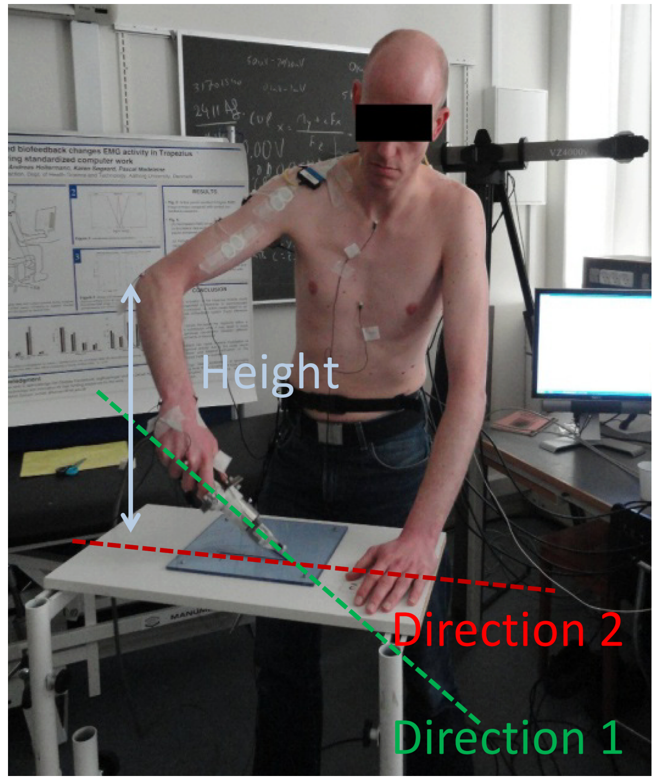

FIGURE 1. EXPERIMENTAL SETUP.

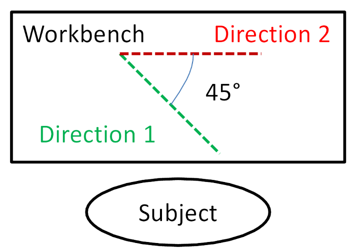

FIGURE 2. CUTTING DIRECTIONS DEFINITION.

The knife has been designed, as shown in figure 3, with respect to the following constraints:

- The blade had to have the shape of real knife. It was assumed that only the tip of the blade was used during cutting;
- The knife had to be handled as a real knife. The handle

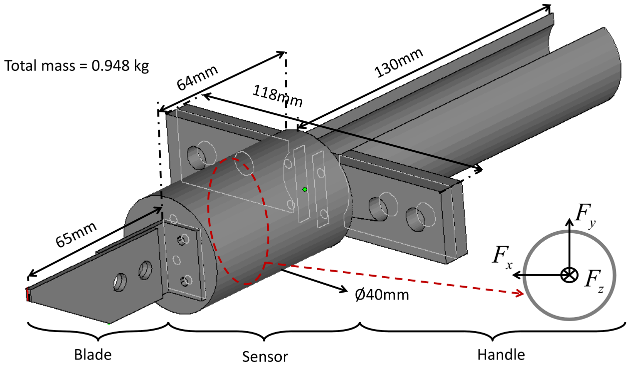

FIGURE 3. INSTRUMENTED KNIFE.

diameter was the same as the one of real slaughter knife and a tennis grip was added to facilitate grasping;

- The knife had to do the same weight as a real knife , however this was not possible due to the weight of the 3D force sensor. The instrumented knife weighted about 0.95 kg. Real knives weigh about $[0.2,\ 0.6]kg$. The weight difference was taken into account in the analysis model;
- The knife had to be rigid enough in order to avoid bending issues during the cutting task. Most parts of the blade were realized in steel ;
- In the same way, all parts were designed to be easily replaced;
- The motion of the knife had to be captured. Three target locations were defined on it, allowing the definition of the global location and orientation of the knife.

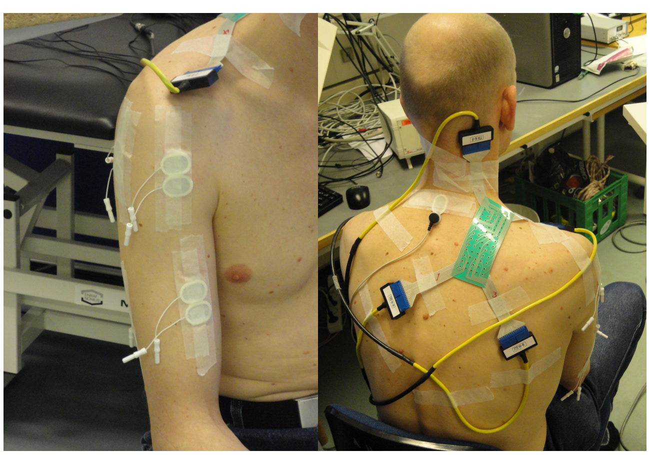

FIGURE 4. SURFACE EMG PLACEMENT.

Surface EMG logging

In order to understand the influence of workplace design parameters on muscle loads, surface electromyographic (EMG) data was collected.

A 64-channel matrix was used to collect the muscle activity of the upper part of the trapezius. The part of the skin covered by the grid was slightly abraded with abrasive paste (Medic-Every, Parma, Italy). The grid was then placed on the muscle with the 4th row aligned on the cervical vertebra C7-acromion line, parallel to the muscle fibre direction [11]. The lateral edge of the grid was 10 mm medial to the identified innervations zone. $30\mu l$ of conductive gel was inserted with a gel dispenser (model Eppendorf, Multiette plus, Hamburg, Germany) into the cavities of the adhesive electrode grid to ensure proper electrode-skin contact. A reference electrode was placed at C7. Moreover, 4 bipolar channels were used to collect EMG from the deltoideus medialis, deltoideus anterior, biceps brachii and triceps long head (Figure 4) with bipolar surface electrodes (Neuroline 720, Ambu, Denmark). Bipolar surface electrodes were aligned (inter-electrodes distance: 2 cm) on abraded ethanol-cleaned skin along the direction of the muscle fibers. Bipolar electrodes were placed with respect to anatomical landmarks. The EMG signals were amplified 2000 times (128-channel surface EMG amplifier, SEA64, LISiN-OT Bioelectronica, Torino, Italy), band-pass filtered [5-500 Hz] and sampled at 2048 Hz (National Instrument, 12 bits acquisition board, Austin, USA).

METHODS

EMG pre-processing

First EMG Signals were rectified and low pass filtered (4 Hz). Then, in order to obtain a good approximation of the activation, a cross-correlation between the resulting cutting force (computed directly from the 3D force signal during the task) and each EMG signal (coming from each EMG electrode) was computed. The maximal correlation obtained for a positive lag (less than 200 milliseconds) was defined from this cross-correlation and the corresponding lag was assumed to be the electromechanical delay between the muscle excitation and the muscle force (figure 5). Delayed EMG signals were assumed to be a good approximation of the muscle activations (the values obtained here were consistent with the ones reported in the literature [12–16], comprised between [30, 150] ms).

The 64-channel matrix signals were not processed in the same way, because the electromechanical delay depends on the spatial location of the measurement channels. Therefore the EMG signals coming from the matrix were not delayed. Moreover, The trapezius muscle is a prime mover and stabilizer of the shoulder [17], and one can assume that its role is mainly postural during this task (as other monitored muscles are prime movers of the upper extremity).

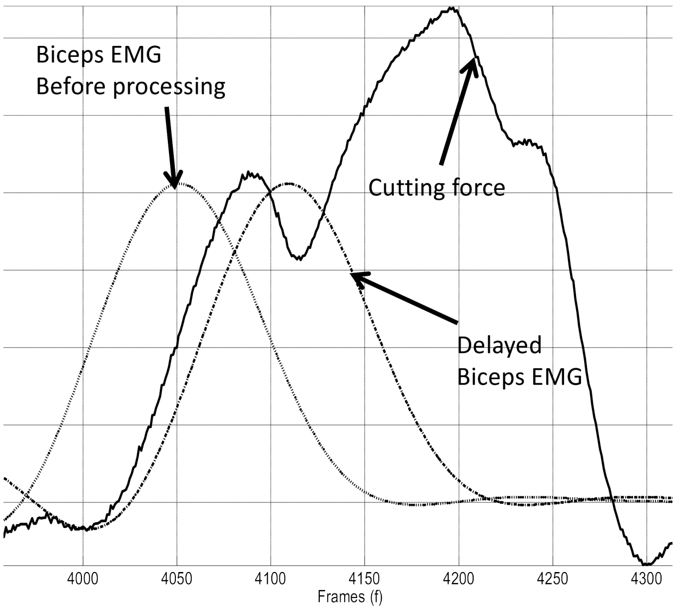

FIGURE 5. EMG DELAY PROCESSING.

Trial processing

To assess the influence of workplace design parameters (workbench height and cutting direction), cutting phases in direction 1 and 2 were isolated trial per trial. Figure 6 shows the different phases reported on a sample trial. Start and end of the cutting phases were identified as a local minimum before a drastic increase (start) or decrease (end) of the cutting force. It also enabled to compute the cutting phases durations, designed as D_j^i in the next section. For this trial, 8 phases for direction 1 and 8 phases for direction 2 were identified.

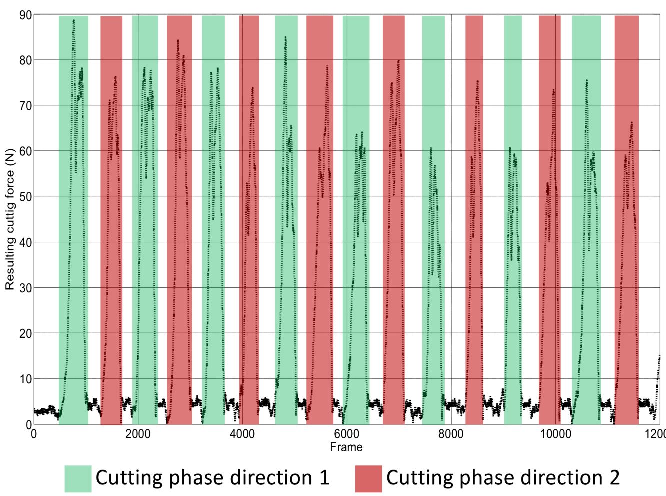

FIGURE 6. CUTTING PHASES IDENTIFICATION.

TABLE 1. TRIAL OUTPUTS.

Output	Unit	Dim
Mean resulting force d1	N	[1x1]
Mean resulting force d2	N	[1x1]
Mean duration d1	s	[1x1]
Mean duration d2	s	[1x1]
Mean biceps activation d1	mV	[1x1]
Mean biceps activation d2	mV	[1x1]
Mean triceps activation d1	mV	[1x1]
Mean triceps activation d2	mV	[1x1]
Mean deltoideus anterior activation d1	mV	[1x1]
Mean deltoideus anterior activation d2	mV	[1x1]
Mean deltoideus medialis activation d1	mV	[1x1]
Mean deltoideus medialis activation d2	mV	[1x1]
Mean Trapezius spatial activation d1	mV	[13x4]
Mean Trapezius spatial activation d2	mV	[13x4]
Mean Trapezius activation d1	mV	[1x1]
Mean Trapezius activation d2	mV	[1x1]

Then, for all of these phases, the mean resulting cutting force and the mean EMG values were computed. Those values were grouped as direction 1 and direction 2 means, and averaged for the whole trial.

For the 64-channel matrix, recording the activity of the trapezius, a mean was done for each bipolar channel during the cutting phases. A spatial [13x4] representation of the mean activation of the trapezius during the task was then obtained. An average of the [13x4] activation map was computed to obtain a similar signal as bipolar electrodes ones. This approach was similar to the one developed in [18].

Table 1 shows the trial outputs obtained after processing (all the means are computed $\pm$ SD).

Relative changes computation

Bipolar electrodes Once the outputs computed for all trials, results were normalized to a $(direction, height)$ reference (corresponding to a $MEAN_{TASK}$ normalization, as described in

[19]). In this study, the chosen reference was ($direction\ 1,\ 0\ cm$). To take into account the fact that the task duration and the mean resulting force was varying from one trial to another, the normalized activations were computed as in equation 1.

$$ {}^{k}R^{i}_{j} = \frac{{}^{k}A^{i}_{j} \cdot \frac{F^{1}_{0} \cdot D^{1}_{0}}{F^{i}_{j} \cdot D^{i}_{j}} - {}^{k}A^{1}_{0}}{{}^{k}A^{1}_{0}} \tag{1} $$

Where ${}^{k}R^{i}_{j}$ was the relative change of the activation ${}^{k}A^{i}_{j}$ of the muscle k at ($direction\ i,\ height\ j\ cm$). F^{i}_{j} was the mean cutting force and D^{i}_{j} was the mean duration of the task at ($direction\ i,\ height\ j\ cm$). The difference in terms of duration and force were taken into account with the confidence factor called α^{i}_{j}, defined in equation 2.

$$ \alpha^{i}_{j} = \frac{F^{1}_{0} \cdot D^{1}_{0}}{F^{i}_{j} \cdot D^{i}_{j}} \tag{2} $$

α^{i}_{j} quantified the difference between two configurations in terms of cutting force and cutting task duration. It represented the amount of work performed by the subject during the cutting task.

64-channel matrix The change of activation of the trapezius was obtained by computing a relative change with regard to ($direction\ 1,\ 0\ cm$) for each channel separately, as reported in equation 3.

$$ {}^{Trap}Rs^{i}_{j}(x,y) = \frac{{}^{Trap}A^{i}_{j}(x,y) \cdot \frac{F^{1}_{0} \cdot D^{1}_{0}}{F^{i}_{j} \cdot D^{i}_{j}} - {}^{Trap}A^{1}_{0}(x,y)}{{}^{Trap}A^{1}_{0}(x,y)} \tag{3} $$

Where (x,y) represents the position of the channel on the matrix. The global change is also a [13x4] spatial representation of the change of activation of the trapezius.A spatial mean was then computed to obtain a single scalar representing change from one configuration to another :

$$ {}^{Trap}R^{i}_{j} = \frac{1}{51} \sum_{x=1}^{4} \sum_{y=1}^{13} {}^{Trap}Rs^{i}_{j}(x,y) \tag{4} $$

Mean spatial entropy during the task and y-position of the barycentre of the activation map were also computed, as defined in [18, 20]. Mean spatial entropy of the activation map is expressing the heterogeneity of the activation patterns, whereas y-position of the barycentre is an indicator of muscle fatigue development in relation with a specific task.

Statistics

Cutting direction (Dir, set to 1 and 2) and table height (Hei, set to $0\ cm$, $-10\ cm$, $-20\ cm$ and $-30\ cm$) were introduced as factors in a full-factorial repeated measure analysis of variance (ANOVA) for the cutting phase characteristics (cutting phase duration (D^{i}_{j}) and mean cutting force (F^{i}_{j})), the bipolar relative variations (biceps (${}^{Bic}R^{i}_{j}$), triceps (${}^{Tri}R^{i}_{j}$), deltoideus anterior (${}^{DAnt}R^{i}_{j}$) and deltoideus medialis (${}^{DMed}R^{i}_{j}$)) and the 64-channel matrix variations (trapezius mean activation change (${}^{Trap}R^{i}_{j}$), Y-position of the barycentre of the activation map (${}^{Bar}Y_{pos}$) and mean spatial entropy (${}^{S}Ent$) as dependent variables.The level of significance was set to $p < 0.05$.

RESULTS

Figure 7 shows a comparison of the activation patterns recorded during a complete cycle (consisting in "Cut in direction 1"-"Hold the knife"-"Cut in direction 2"-"Hold the knife") at 4 different workbench heights for subject 1. Activations were normalized to the maximum recorded - all cycles pooled. Trapezius activation corresponds to the average of the [13x4] map at each frame. Patterns have similar shape from one height or one direction to another, but amplitudes vary a lot. Deltoideus anterior seems to be involved in the motion (as its action tends to stabilize the cutting force level after its generation), whereas other muscles have a role in the cutting force generation (as their patterns are synchronised with the cutting force arise).

Table 2 shows the results of the full-factorial repeated measure analysis of variance conducted as presented in the methods section. Significant results are highlighted in bold and followed by *. Cutting phase characteristics analysis shows that the resulting cutting force F^{i}_{j} is significantly influenced by the cutting direction and the workbench height, whereas duration D^{i}_{j} is not. Bipolar relative variations are also affected by the cutting direction (${}^{Bic}R^{i}_{j}$, ${}^{Tri}R^{i}_{j}$), the workbench height (${}^{Bic}R^{i}_{j}$, ${}^{Tri}R^{i}_{j}$, ${}^{DAnt}R^{i}_{j}$), or the interaction of both factors (${}^{Bic}R^{i}_{j}$,${}^{DMed}R^{i}_{j}$). At last 64-channel variations are influenced by the cutting direction (${}^{Trap}R^{i}_{j}$, ${}^{Bar}Y_{pos}$ and ${}^{S}Ent$). Entropy ${}^{S}Ent$ is also affected by the workbench height.

An overview of the cutting tasks mean durations and mean cutting intensities with regard to the cutting direction and the workbench height is presented figure 8. The mean cutting force remains in a range in accordance with [7, 10], i.e. between 30 and 50 N in average. Also, duration remains constant in average

TABLE 2. WITHIN-SUBJECT REPEATED MEASURES ANOVA.

Dependent variables	**Factors**					
	Direction (Dir)		Height (Hei)		Dir **x** Hei	
	F	p	F	p	F	p
Cutting characteristics						
D_j^i	$0,95$	$0,37$	$0,91$	$0,46$	$0,29$	$0,83$
F_j^i	**26,2***	$0,002$	**5,9***	$0,005$	$1,24$	$0,32$
Bipolar relative variations						
${}^{Bic}R_j^i$	**36.51***	< 0.001	**63.2***	< 0.001	**3.27***	0.04
${}^{Tri}R_j^i$	**17.70***	0.006	**18.11***	< 0.001	2.89	0.06
${}^{DAnt}R_j^i$	3.33	0.12	**43.1***	< 0.001	0.59	0.63
${}^{DMed}R_j^i$	$0,76$	0.42	2.61	0.08	**5,06***	$0,01$
64-channel variations						
${}^{Trap}R_j^i$	**45.07***	< 0.001	2.5	0.09	2.18	0.13
${}^{Bar}Y_{pos}$	**9.32***	0.02	2.28	0.11	0.29	0.83
${}^{S}Ent$	**15.71***	0.007	**4.52***	0.02	2.33	0.11

whereas exerted cutting force seems to increase when the workbench height decreases, and remains higher in direction one than in direction 2, in accordance with the ANOVA results shown in table 2.

Figure 9 shows the relative change in muscle activations recorded with the bipolar electrodes (biceps brachii, triceps long head, deltoideus anterior and deltoideus medialis) with regard to the workbench height for both cutting directions (direction one in green, direction 2 in pink). For biceps, triceps and deltoideus anterior, activations trend to decrease when the workbench height decreases independently of the subject, in accordance with the ANOVA results (table 2). For the deltoideus medialis, activation increase in average when the workbench height decrease. However, according to the ANOVA results (table 2), the results are only affected by the combination between height and direction, and are deeply related to the way the subject is performing the task. Direction has also an influence on biceps and triceps activation. Direction 1 leads to less activation than direction 2.

Figure 10 shows the relative change of upper trapezius activation recorded with the 64-channel matrix (resp. trapezius relative activation change, y-position of the barycenter, and average matrix entropy). The relative variation of trapezius activation highlights the inter-subject variability. The cutting direction 1 leads to less activation than cutting direction 2. Y-position of the barycentre presents a significant shift in the caudal direction for the cutting direction 1. Average matrix entropy is affected by both direction and height. THe entropy increases significantly when the workbench height decreases, and direction 1 leads to an higher entropy than direction 2.

Results indicates that :

- Direction 1 leads in general to lower muscle activation levels than direction 2. Moreover, direction 1 tends to increase the barycentre y-position shift of the trapezius activity and the average matrix entropy.
- Height decrease tend to lower the muscle activation levels, excepted for the deltoideus medialis, even if for this muscle the differences between subjects prevents a firm conclusion. Height also enables to increase the trapezius activation spatial entropy.

DISCUSSION

This study aimed at analysing the influence of the workbench height and the cutting direction on muscle activation levels. An trend analysis with regard to a configuration of reference was conducted. The trends of cutting force, cutting duration and muscle activation levels of prime movers muscles and

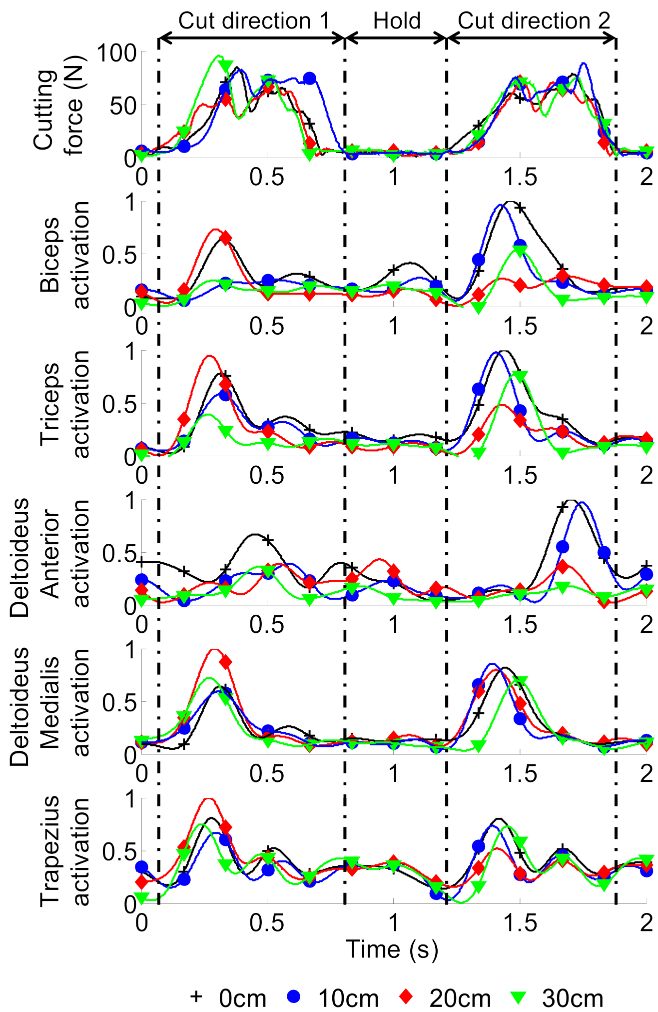

FIGURE 7. COMPARISON OF TRIAL-NORMALIZED ACTIVATION PATTERNS FOR A COMPLETE CYCLE WITH REGARD TO THE WORKBENCH HEIGHT (SAMPLE SUBJECT 1).

postural muscles (respectively biceps brachii, triceps long head, deltoideus anterior, deltoideus medialis and trapezius) revealed that cutting direction and height have a significant influence on muscle activation levels. Individual differences in motor control strategies were also found.

The task described here is not an exact copy of a real meat cutting task, but involves some of the well-acknowledged physical risk factors associated with this work, like repetitive arm movements, strenuous, relative short work cycle duration and static posture [2, 3]. As the phases within the task where not standardized in terms of time, duration really depends on the subjects appreciation (see figure 8). Those differences can explain the reported activation for the deltoideus medialis during the task. Most of the variance observed for this activation is ex-

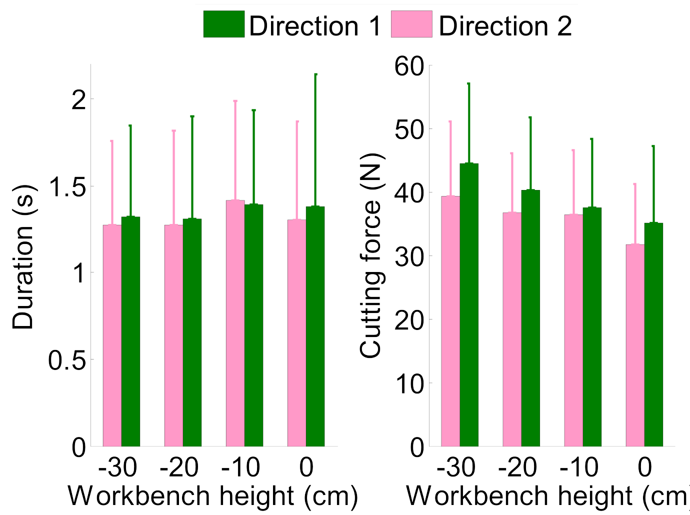

FIGURE 8. TASKS DURATIONS AND AVERAGE CUTTING FORCES FOR SUBJECT 1.

plained by the subject motor strategies and not by the height and direction parameters as expected.

Recorded activation patterns (figure 7) showed that biceps, triceps, deltoideus medialis and trapezius are involved in the force generation, whereas deltoideus anterior is mostly activated at the end of the cutting phases, playing a role in the force stabilization. For the trapezius, this observation is in contradiction with the fact that it is commonly considered as playing an important role in supporting the body posture and in movements of the head and shoulders during a number of tasks, e.g. stabilization of the shoulder joint to allow precise manipulations. Deltoideus anterior and biceps have a non-negligible activation during the cutting phases (higher than during holding phases), whereas their action is mechanically counter-productive (they counter the joint torques necessary to generate the cutting force). As those muscles activate with regard to the synergistic muscles (that are the triceps and deltoideus medialis), this co-contraction can be assumed as an action of stabilization of the knife during the task. Subjects had to maintain the knife in the grooves during the cutting phases. It required to maintain a level of co-contraction to increase the stability of the upper limb during the task, as it has been already shown in [21, 22]. Co-contraction also increases limb stiffness, and minimizes the perturbing effects of forces arising from limb dynamics [23]. It corresponds to the co-contraction role reported in several EMG studies about control of the upper extremity [21, 24–29].

As motor control strategies are affected by task learning [30, 31], experience within a task realization mostly leads to a reduction of co-contraction levels. The hypothesis is that the Central Nervous System (CNS) regulates co-contraction and hence

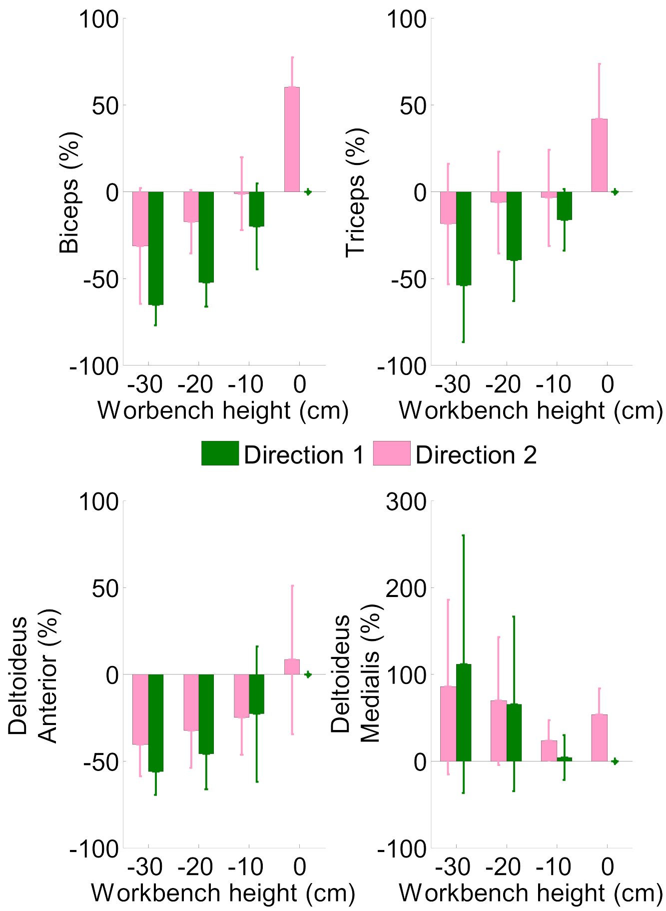

FIGURE 9. RELATIVE VARIATIONS OF RECORDED BIPOLAR ACTIVATIONS.

limb stiffness as a way to facilitate movement accuracy. Co-contraction gradually decreases with practice because the CNS tends to define an internal motor strategy implying only synergistic muscles [21]. This assumption is in line with previous studies of standardized meat cutting tasks processes. In [32], results showed that workers with experience have a motor control strategy implying less variability, a smaller range of motion and more complexity than inexperienced workers. On the contrary, [33], experienced workers compared with novices were characterized by large size of variability. This aspect is of importance as motor strategies of experienced workers can be radically different from the ones reported here. This issue needs to be taken into account when changing parameters such as workbench height.

Assessing kinematics during the task can be very helpful to understand the recorded changes. Actually, the analysis of the shoulder motion during the task show important changes in shoulder internal rotation for direction 2 [34]. It can explain that for equivalent levels of resulting forces, direction 1 is asking less

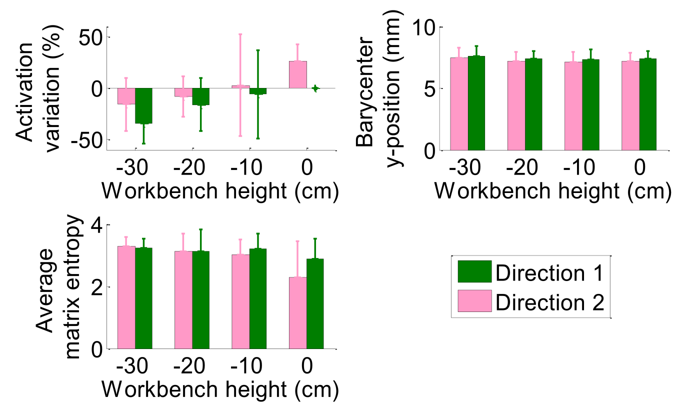

FIGURE 10. RELATIVE VARIATIONS, Y-POSITION OF BARYCENTER AND AVERAGE MATRIX ENTROPY OF TRAPEZIUS SPATIAL ACTIVATION.

muscle activation than direction 2. It also explains why the deltoideus anterior is active during the end of the cutting events in direction 2, as it is a prime mover of the shoulder internal rotation.

The main limitation of the present study concern population size. The full-factorial repeated measures ANOVA conducted in the study is based on data following a normal distribution. This condition was not fulfilled and resulted in type II error. To circumvent that limitation, we only discussed the reported significant differences. A larger population size has to be investigated to validate the results of this first study.

CONCLUSION

In this study, the changes of recorded EMGs during meat cutting tasks with regard to two workplace design parameters, i.e. the table height and the cutting direction, were investigated. A complete experimental set-up, enabling the synchronous recording of activations of muscles involved in the upper extremity and cutting force was described. Then a method to analyse the relative change of muscle activations with respect to the workplace configuration was introduced. Results of an experimentation involving seven subjects showed that workbench height and cutting direction have both an influence on muscle loads. Limitations were reported in terms of population and subjects level of experience. Finally, this method of analysis will be used to validate musculoskeletal models, as presented in [35] with hybrids methods, as presented in [36, 37]. As quantitative assessment of such models remains difficult, trend analysis can be a serious alternative to evaluate their accuracy [38]. The use of musculoskeletal models as motion analysis tools, coupled with Virtual Reality tools [39] might be an important opportunity for a systematic assessment of ergonomics during the design of a workplace.

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