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Biomechanical requirements of meat cutting tasks: a pilot study quantifying tasks sustainability and assistance required at the wrist

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Abstract

The meat processing industry is particularly affected by distal upper limb musculoskeletal disorders. This pilot study aims at proposing a methodology able to quantify biomechanical requirements of meat cutting tasks at butchers' dominant wrist and, when necessary, at estimating the assistance needed to reach sustainability. Six professional butchers repeatedly cut pieces of pork. Joint angles were recorded using a motion capture system, cutting forces using an instrumented knife. Sustainability was computed by the maximal acceptable effort method. Assistance requirements were computed for isolated stressful exertions and for overall work cycle sustainability. Five butchers exceeded the sustainability threshold for wrist flexion. Ulnar or radial deviation torques were excessive for 2 and 3 of them, respectively. Extension torques were sustainable. The peak assistive torque for isolated exertions was at most 1.1Nm, 1.6Nm and 1.1Nm, and the percentage of assistance for overall sustainability was at most 60%, 56% and 56% for wrist flexion, ulnar and radial deviation, respectively.

Keywords

wrist; occupational musculoskeletal disorders; muscle strength; range of motion, articular; biomechanical specifications

Highlights

- Meat cutting tasks exceeded sustainability threshold in wrist flexion
- Meat cutting tasks were sustainable in wrist extension

- 32 - Meat cutting tasks were sometimes not sustainable in ulnar or radial deviation
- 33 - Fast-paced nature of tasks affected subjects more than isolated stressful exertions
- 34

35 **1. INTRODUCTION**

36 Work-related Musculoskeletal Disorders (MSDs) are a major public health issue (de Kok et al., 2019).

37 The meat processing industry is one of the most affected industrial sectors, as MSDs prevalence is 10
38 to 15 times higher than in the general population (Lemerle & Chicot, 2018). Nordander et al. (2009)
39 reported high prevalence of hand, wrist, and elbow MSDs among male meat cutters. Furthermore,
40 Moore & Garg (1994) reported that hand and wrist MSDs prevailed (77%) over elbow MSDs (23%)
41 among distal MSDs (n=104), in a pork processing facility employing 1100 individuals. Consequently,
42 attempts to mitigate the risk of MSDs are suitable, especially at the distal upper limb.

43 Several risk factors for MSDs have been identified in the workplace, such as physical workload (e.g.,
44 high forces, repetition, awkward postures), organizational (e.g. task and job duration, recovery time),
45 environmental (e.g., inappropriate lighting, low temperatures, noise), psychosocial (e.g., job demands,
46 job content) and individual (e.g., individual skills, health problems) factors (Karasek et al., 1981; *NF*
47 *ISO 11228-3*, 2007). Similarly, in the meat processing industry, several epidemiologic studies have
48 found statistical links between the physical workload and MSDs incidence or prevalence (Frost et al.,
49 1998; Moore & Garg, 1994; Nordander et al., 2009). Detailed ergonomics and biomechanical
50 description of work organization and meat cutting tasks have been provided (Arvidsson et al., 2012;
51 Silvin, 1999). Several studies attempted to understand the effect of work organization or knife
52 sharpening in the meat cutting industry MSD issues (Karlton et al. 2016, Savescu et al. 2018). A number
53 of studies focused on the effect of various additional parameters influencing risk factors e.g., the use
54 of a hand tool like a knife (Claudon & Guiguet, 2003; Gorsche et al., 1998), the characteristics of the
55 knife (Marsot et al., 2007; Tirloni et al., 2020), or the effect of the workbench height (Pontonnier et
56 al., 2012). A recent study proposed in situ evaluation of physical risk factors (Villalobos & Mac Cawley,
57 2022). Attempts have been made to mitigate those risk factors: improved ergonomics of workstations
58 (R. W. McGorry et al., 2004; Pontonnier et al., 2014), automation (Arvidsson et al., 2012; Tappin et al.,

59 2008). These attempts are still struggling to significantly enhance the work conditions, especially due
60 to the industrial constraints that are still prevalent. To further reduce physical stress in meat cutting
61 industry, exoskeletons or cobots (Maithani et al., 2021) delivering an assistive force to the user during
62 the task execution can also be considered (Chander et al., 2022; Tomezzoli et al., 2023). However,
63 such systems raise numerous issues, such as their control, the adaptability to the user, possible
64 undesired effects (Pontonnier et al., 2021; Tomezzoli et al., 2023). Moreover, such systems may have
65 to be designed with regard to the biomechanical requirements related to the task (Chander et al.,
66 2022). According to Tirloni et al. 2021, the most recent measures of meat cutting forces using an
67 instrumented knife are almost one decade old.

68 The use of a single aggregated indicator that globally reflects the biomechanical risk factors influencing
69 the appearance of MSDs is interesting to assess the sustainability of a task and to forecast the effect
70 of ergonomic interventions or assistive devices. Although analysis of specific risk factors like joint
71 angles and torques are mandatory to understand in depth the biomechanical demand for a task, an
72 aggregated indicator is also useful to specify the assistance requirements of an exoskeleton. The OCRA
73 index (Occhipinti & Colombini, 2007), the Strain Index (Moore & Garg, 1995) and the TLV (ACGIH,
74 2016) are prominent methods to summarize the risk of MSDs for the upper limbs in repetitive tasks
75 through one single indicator (*NF ISO 11228-3*, 2007) . The current version of the TLV (ACGIH, 2016)
76 relies on the maximal acceptable effort (MAE) model described by Potvin (2012), after refitting the
77 model to enable higher maximal efforts for repetitive tasks occupying more than 50% of the work
78 cycle (Abdel-Malek et al., 2020). The MAE is the maximal effort sustainable for tasks performed for 8
79 hours per day, determined experimentally through psychophysical studies. As the MAE method
80 targeted fatigue phenomena at the distal upper limb, which is a frequent MSDs location in butchers
81 (Nordander et al., 2009), this method is a good candidate to assess meat cutting tasks in terms of
82 physical demand in this population. A mathematical relationship between the MAE and the duty cycle
83 (DC), defined as the ratio of the task duration within a cycle to the work cycle time (CT), was proposed.
84 Based on this relationship, the assistive torque required to reduce the effort to the level of MAE and

85 the rest required (*RR*) after a given task can be computed. For a work cycle consisting of multiple
86 tasks, the cumulative rest required can also be computed by summing up the *RR* for each task (Gibson
87 & Potvin, 2017). To the best of our knowledge, the MAE method has not been used in application to
88 meat cutting tasks before. The current study is an exploratory study aimed at evaluating the
89 biomechanical requirements of meat cutting tasks at professional butchers' dominant wrist, by the
90 cutting force, joint angles, joint torques, along with an estimation of the overall sustainability of the
91 task and, when needed, theoretical assistive torque required to reach sustainability using the MAE
92 model.

93

94 **2. METHODS**

95 **2.1 Experiments**

96 Six professional butchers, free from any musculoskeletal pain or discomfort in the last 6 months and
97 fully operational in the plant, participated in the experiments in a motion analysis laboratory. Three
98 pork pieces and one beef piece cutting tasks (Table 1) were selected by the partner meat processing
99 plant (COOPERL, France) regarding activities with frequent sick-leave disrupting the company. In this
100 work, only the pork trials were investigated due to limited beef trials, which had only two repetitions
101 each for two subjects. The study was approved by a national ethics committee (Comité Opérationnel
102 d'Evaluation des Risques Légaux et Ethiques, COERLE, n° 2021-07). Subjects signed an informed
103 consent form prior to participating in the experiment.

104 **2.2 Equipment**

105 Motion capture data was recorded at 200Hz using an optoelectronic system with 32 cameras (Qualisys
106 Track Manager (QTM) 2021). 40 reflective markers were placed on the subject and 4 on the knife
107 (Figure 1). Cutting force and moments were measured with a wireless instrumented knife (6 degrees
108 of freedom (dof) force sensor, ATI Mini45-E Transducer, mounted between the handle and the
109 replaceable blade, 500Hz). The partner meat processing plant supplied two blades with different

110 lengths of 11cm (shown in Figure 1; the figure shows the distance between the blade tip and the
 111 sensor reference frame and not the blade length) and 19.2cm that are typically used in the selected
 112 tasks. The subjects preferred the shorter blade for all pork trials and the longer blade for beef trials.
 113 Forces and moment applied to the worktable, ground reaction forces and EMG signals of several upper
 114 limb muscles were recorded (not used in this study). All signals were synchronized with the motion
 115 capture system through the Transistor-Transistor logic (TTL) synchronization signal of the motion
 116 capture system. The joint strength at the wrist was measured using a Con-Trex MJ® isokinetic
 117 dynamometer (CMV AG, Dübendorf, Switzerland), following the constructor recommendation for
 118 isometric wrist strength assessment.

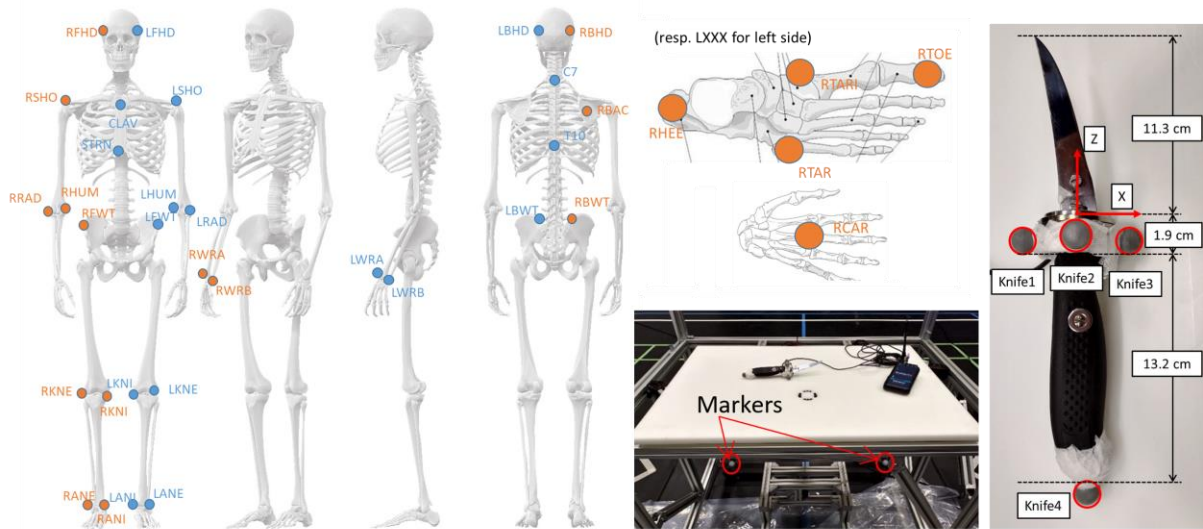
119 *Table 1. Subject demographics and cutting trials performed.*

	Sex	Height ¹ (cm)	Age (years)	Weight ¹ (kg)	Dominant Hand	Experience (years)	Piece cut	Repetitions
S1	M	172	50	82.2	Right	27	Pork belly side 1 (PB_1)	5
S2	M	180	50	76.0	Right	21	Pork belly side 2 (PB_2)	5
S3	M	178.5	47	86.1	Right	27	Pork spare rib (PSR)	5
S4	M	176	40	78.4	Right	11	Pork spare rib (PSR)	5
S5	M	172.5	48	53.6	Right	32	Pork Shoulder (PS) and Beef collar (BC) ²	5xPS then 2xBC ²
S6	M	179.5	21	60.4	Right	5	Beef collar (BC) ² and Pork Shoulder (PS)	2xBC ² then 5xPS

120 ¹Height and weight is with shoes. ² Not included in this study

121

122



123
124 (a)



125
126 (b)

127 *Figure 1: (a) Marker placement on the subject (markers on the right side are shown in orange, while*
 128 *those on the left side and centre are shown in blue). Additionally, markers located on the knife and*
 129 *table (one marker on the table was on the opposite and is not visible in the photo). The coordinate*
 130 *system on the knife shows the force sensor origin. (b) a subject in action during a pork belly cutting*
 131 *trial (left), and a maximal isometric wrist radial deviation strength test (right).*

132

133

134 **2.3 Protocol**

135 After being briefed, the height and weight of the subject were recorded. Next, isometric maximal joint
136 strength in wrist flexion (WF), wrist extension (WE), ulnar deviation (UD), and radial deviation (RD) of
137 the dominant arm were measured with the dynamometer, in the posture recommended by the
138 ergometer manufacturer (seated on the chair, strapped to fix shoulder, arm and trunk, shoulder at
139 rest, elbow flexed at 90°, forearm pronated at 0° or 90° depending on the degree of freedom assessed,
140 wrist at rest), for five seconds with verbal encouragements. The subject was then equipped with
141 motion capture markers and EMG electrodes. They wore protective equipment (chainmail apron and
142 sleeve for the non-dominant arm), markers located on the sternum, pelvis front left and right, non-
143 dominant wrist and hand were placed on top of the protective equipment.

144 Next, a range-of-motion (ROM) trial was performed for geometrical calibration of the biomechanical
145 model of the subject. The piece to be cut was placed on the table and weighed by the force sensor.
146 Then, the meat cutting trials were performed. To facilitate data processing, the subject marked the
147 beginning and end of the cutting task by tapping the knife on the table. The knife was sharpened as
148 and when deemed necessary by the subjects. Five repetitions were planned for each subject.
149 However, one repetition each from Subject 1 and Subject 2 could not be used due to technical issues
150 during the recording of the motion capture data, with no data saved.

151 **2.4 Data analysis**

152 2.4.1 Inverse kinematics and dynamics analysis

153 Marker trajectories were processed in QTM and low pass filtered (4th order Butterworth with no phase
154 shift at 10Hz). All force data was resampled to the mocap frequency. All trials were cropped to isolate
155 the cutting task using the start and end taps in the cutting force. A biomechanical model of the upper
156 limb (3 segments, 7 degrees of freedom), available in the motion analysis library CusToM (Muller et
157 al., 2019), was used in this work. The model of the subject was scaled according to the height of the
158 subject and the weight including the equipment (5.5 kg). The ROM trial was used for geometrical

159 calibration of the model (Puchaud et al., 2020). The knife force was applied to the hand of the subject
160 after transformation into the global reference frame through the markers located on the knife. Wrist
161 joint angles and joint torques were computed using CusToM. Further, the percentage durations of
162 joint angles and joint torques between WF and WE, and UD and RD during the cycle were also
163 computed. The grip of the knife was observed from the video recording of the trial.

164 2.4.2 Sustainability analysis

165 To perform the sustainability analysis, it was required to normalize the joint torques obtained from
166 the inverse dynamics analysis to make them comparable to the MAE model. The normalized effort
167 required by the subject for meat cutting was computed as the ratio of the joint torque required at the
168 wrist to the joint (maximal) strength of the subject in the corresponding direction. The changes in the
169 joint strength due to changes in joint angle and velocity were modeled by the torque-angle-velocity
170 (TAV) envelopes for the wrist (Xia & Law, 2015). The envelopes were scaled by the ratio of the subject's
171 isometric strength in the neutral posture to the strength from the TAV envelope at zero angle and
172 velocity to obtain one $TAV(q, \dot{q})$ envelope per exertion type (WF, WE, RD and UD respectively),
173 depending on the joint position q and velocity \dot{q} .

174 The cycle time (CT) for the trial performed by the subjects was computed as the duration between
175 the starting and ending tap recorded by the subject. The largest CT from the repetitions performed
176 by a subject was considered as the CT for the task. However, if the second largest CT was less than
177 75% of the largest CT , the repetition with the largest CT was excluded from the sustainability analysis
178 as an outlier to possibly account for an unfamiliar laboratory environment and measuring equipment
179 for the subjects. This affected one repetition each from Subject 1 and Subject 3. All individual cutting
180 events (also called as exertions) in a given trial were defined by blocks of time with cutting force
181 continuously greater than 5N. Duty Cycle (DC_i (%)) of an exertion i was computed as the ratio of the
182 Time of Exertion TE_i to CT .

183 Since the peak effort lasted for a fraction of the duration of an exertion, often consisting of several
 184 cutting strokes, an equivalent effort ($EqEff_i$) was computed as the peak of a bell curve of equivalent
 185 area under the curve (equal impulse) as that of the effort in the exertion i , during the same TE_i . The
 186 joint torques issued from the inverse dynamics were processed the same way, resulting in equivalent
 187 joint torque per exertion ($EqJT_i$).

188 The MAE_i (%) for an exertion i was computed using the equation:

$$MAE_i = 1 - [DC_i - 1/28800]^{0.24} \quad (1)$$

189 28800 is the number of seconds in a standard 8-hour workday and implied that $MAE = 100\%$ for $DC \leq$
 190 1s/workday as defined in Potvin 2012.

191 The sustainability of each exertion was checked in isolation, for the four exertion directions at the
 192 wrist. If the $EqEff_i$ exceeded the MAE_i for a given exertion, the exertion and work cycle were
 193 considered unsustainable. The assistive torque $Tass1_i$ needed to make the exertion i sustainable is
 194 denoted as $Tass1$ and was computed as the difference in percentage of $EqEff_i$ between $EqEff_i$ and
 195 MAE_i , multiplied by the equivalent joint torque of exertion i $EqJT_i$.

$$Tass1_i = \begin{cases} 0, & \text{if } EqEff_i \leq MAE_i \\ (EqEff_i - MAE_i)/EqEff_i * EqJT_i, & \text{if } EqEff_i > MAE_i \end{cases} \quad (2)$$

196

197 The rest required per exertion RR_i was computed based on the TE_i with the following equation
 198 (Gibson & Potvin, 2016):

$$RR_i = \frac{TE_i}{[1 - EqEff_i]^{4.167} + 1/28800} - TE_i \quad (3)$$

199 Despite each exertion being sustainable in isolation, a work cycle can be unsustainable due to a lack
 200 of adequate recovery period. The rest available in the work cycle, RA_c (s), is computed as the difference
 201 between the CT and sum of the duration of all the n exertions of the cycle:

$$RA_C = CT - \sum_{i=1}^n TE_i \quad (4)$$

202 A work cycle was considered unsustainable if RR_C (rest required per cycle, computed as the sum of
 203 the RR_i) exceeded RA_C . If the work cycle was unsustainable, the $EqEff$ of all the exertions were
 204 reduced by a constant percentage δ of their current value such that RR_C was equal to RA_C . This
 205 percentage reduction was converted to assistive torque for each exertion i , denoted as $Tass2_i$, by
 206 multiplying δ by $EqJt_i$.

207

$$Tass2_i = \begin{cases} 0, & \text{if } RR_C \leq RA_C \\ \delta * EqJt_i, & \text{if } RR_C > RA_C \end{cases} \quad (5)$$

208 Naturally, a work cycle with at least an exertion with $EqEff_i$ greater than MAE_i was unsustainable as
 209 RR_C would exceed the RA_C . In such cases, computation of δ and $Tass2_i$ did not include $Tass1_i$.

210 In the results, the average of the maximum values of $Tass1_i$ and $Tass2_i$ considering all the exertions
 211 in the work cycle are presented for each subject. The above calculations for sustainability, i.e., RR_C ,
 212 $Tass1$, and $Tass2$ were computed independently for each exertion direction at the wrist.

213 3. RESULTS

214 There were differences in the laboratory CT for subjects performing the same task. However, the
 215 exertion frequencies were comparable for the subject pairs except for Subjects 3 (38.4 exertions per
 216 minute) and 4 (24.8 exertions per minute) (See Supplementary Material). The type of measurements,
 217 and subsequently of assistance are discussed. Wrist flexion angle exceeded the safety threshold of 45°
 218 (NF ISO 11228-3, 2007) for one subject, wrist extension for 5 subjects, ulnar deviation for 5 subjects
 219 and radial deviation for 3 subjects. Most of the work cycle was spent with the wrist flexed in ulnar
 220 deviation for cutting pork belly side (2 subjects), with wrist extended in radial deviation for cutting
 221 pork shoulder (2 subjects); both patterns were encountered for cutting pork spare rib (1 subject each)
 222 (Table 2). Peak resultant cutting force varied between $58 \pm 7N$ and $105 \pm 11N$. Flexion joint torque was
 223 over-represented across time for every subject except Subject 4, irrespective of the flexion-extension

224 joint angle. Conversely, radio-ulnar deviation and torque directions seemed cross-coupled e.g.,
 225 predominant radial torque being associated with predominant ulnar deviation (Table 2). Histograms
 226 of joint torques and efforts as functions of joint angles displayed various profiles depending on tasks,
 227 subjects and joint angles (see Figure 2C to F and Figure 3C to F for Subject 1; see supplementary
 228 material for the other subjects).

229 Subjects 1 and 2 used a forward knife grip while Subjects 5 and 6 used predominantly the edge-in
 230 reverse knife grip. Subjects 3 and 4 used both grips during the trial, with Subject 3 starting with the
 231 forward knife grip and switching to the edge-in reverse knife grip midway through the trial. Instead,
 232 Subject 4 started with the edge-out reverse knife grip, switched to forward knife grip, and finished
 233 with edge-in reverse knife grip (Figure 4).

234 *Table 2. Wrist postures and exertion: mean (+/- SD) of peak and average joint angle and joint torque*
 235 *values, and percentage of the work cycle that the subjects spent between different wrist postures and*
 236 *exertion directions*

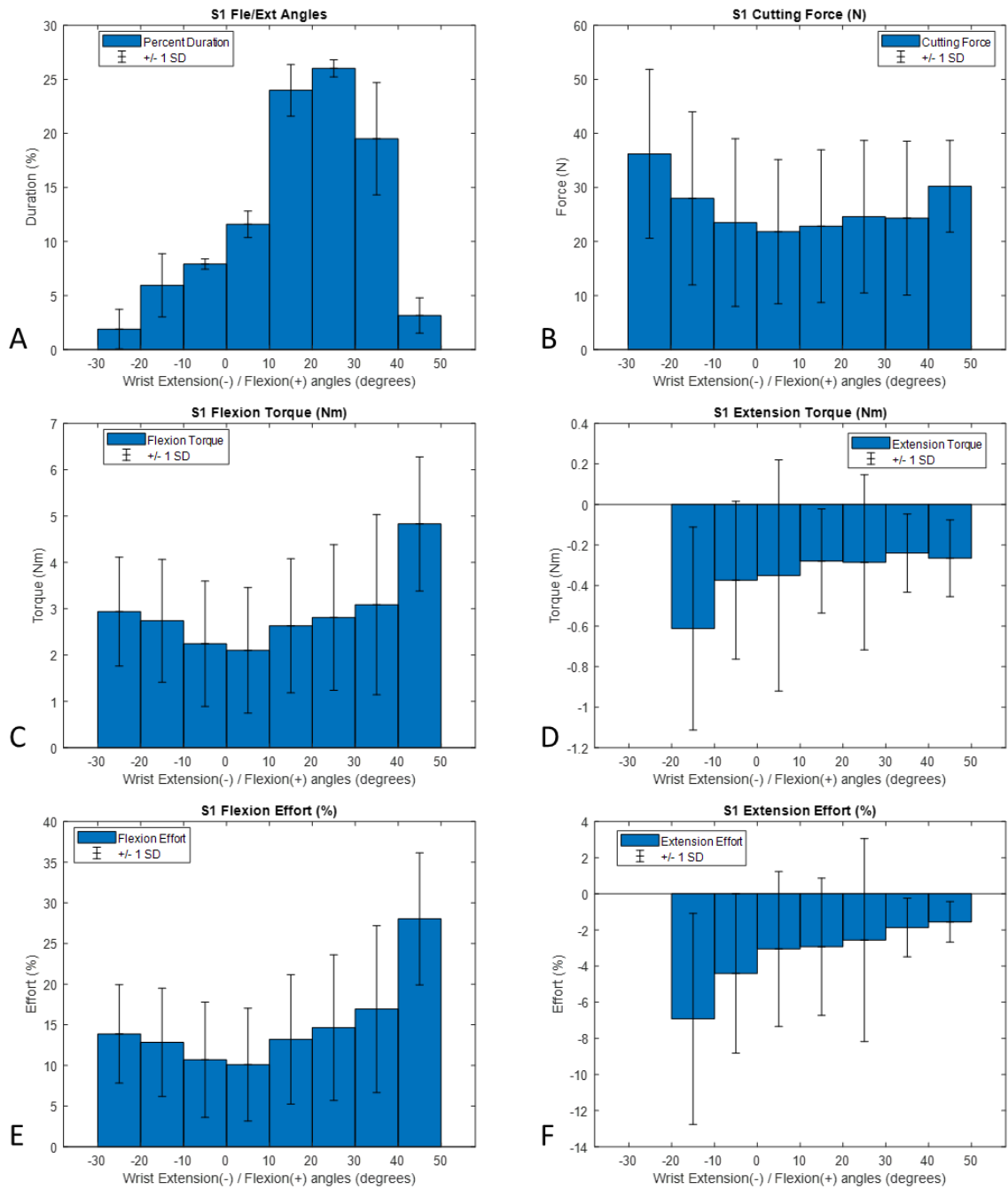
Subject	Joint Angle				Joint Torque			
	Flexion	Extension	UD	RD	Flexion	Extension	UD	RD
	Peak value (°)				Peak value (Nm)			
S1	45 (2)	-27 (3)	35 (1)	-9 (0)	7.9 (1.1)	-1.7 (0.7)	4.2 (3.1)	-6.2 (0.8)
S2	42 (3)	-45 (8)	41 (1)	-5 (2)	9.9 (1.2)	-1.2 (0.4)	3.4 (1.1)	-6.5 (1.3)
S3	41 (4)	-51 (2)	27 (3)	-8 (1)	8.0 (0.6)	-1.4 (0.3)	6.8 (0.6)	-8.5 (0.9)
S4	13 (11)	-57 (2)	26 (3)	-30 (1)	5.8 (1.4)	-3.0 (0.5)	5.5 (0.4)	-4.1 (1.1)
S5	39 (7)	-59 (2)	25 (2)	-18 (2)	9.6 (1.3)	-1.6 (1.2)	9.7 (0.7)	-1.3 (1.0)
S6	44 (7)	-64 (3)	20 (1)	-21 (1)	8.3 (1.2)	-5.1 (0.6)	8.4 (0.7)	-4.1 (1.0)
	Average value (°)				Average value (Nm)			
S1	22 (1)	-10 (2)	22 (1)	-6 (1)	2.8 (0.4)	-0.3 (0.1)	0.8 (0.2)	-1.7 (0.2)
S2	13 (2)	-10 (1)	23 (2)	-2 (1)	2.4 (0.2)	-0.3 (0.1)	0.8 (0.3)	-1.7 (0.2)
S3	23 (3)	-31 (3)	14 (1)	-3 (1)	2.7 (0.1)	-0.4 (0.1)	2.4 (0.1)	-3.2 (0.1)
S4	7 (7)	-30 (2)	15 (1)	-17 (1)	1.7 (0.3)	-0.7 (0.1)	1.9 (0.3)	-1.4 (0.3)

			11				2.9	-0.3
S5	17 (4)	-33 (2)	(2)	-8 (1)	3.0 (0.3)	-0.4 (0.3)	(0.1)	(0.3)
				-11			2.3	-0.7
S6	16 (3)	-26 (3)	9 (2)	(1)	2.2 (0.2)	-1.2 (0.2)	(0.3)	(0.1)
	Duration (%)				Duration (%)			
S1	84 (5)	16 (5)	96	4 (2)	94 (1)	6 (1)	16 (4)	84 (4)
			(2)					
S2	65 (6)	35 (6)	93	7 (2)	94 (3)	6 (3)	26 (6)	74 (6)
			(2)					
S3	62 (8)	38 (8)	83	17 (4)	92 (2)	8 (2)	36 (7)	64 (7)
			(4)					
S4	6 (6)	94 (6)	34	66 (5)	50 (5)	50 (5)	43 (6)	57 (6)
			(5)					
S5	29 (12)	71 (12)	34	66 (9)	93 (3)	7 (3)	90 (7)	10 (7)
			(9)					
S6	26 (3)	74 (3)	32	68 (4)	84 (5)	16 (5)	84 (2)	16 (2)
			(4)					

237 *Yellow cells: joint angles > ergonomic thresholds, respectively 45°, 45°, 20° and 15° for flexion, extension, ulnar and radial*
238 *deviation (NF ISO 11228-3, 2007). UD: ulnar deviation. RD: radial deviation*

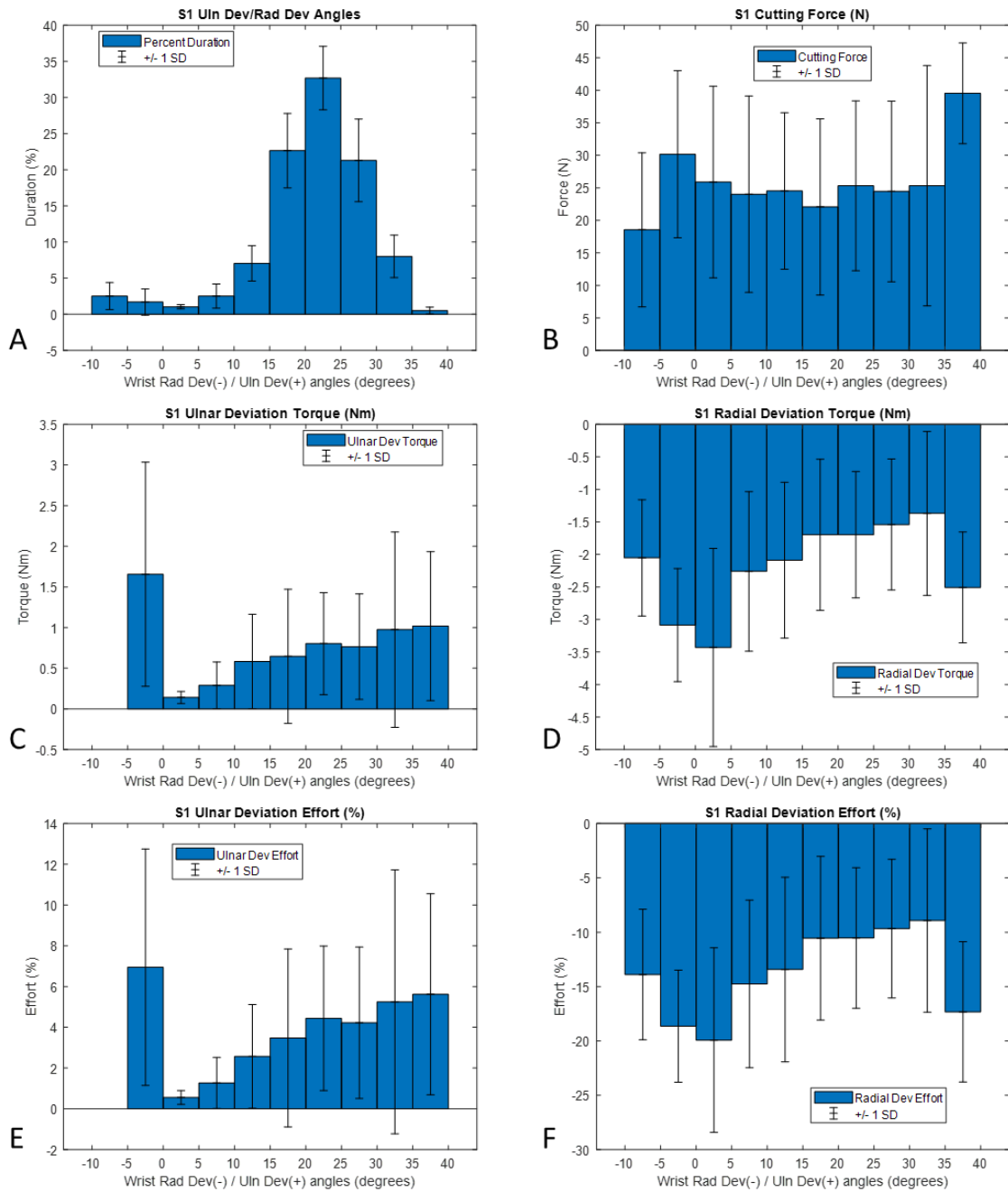
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241

242 *Figure 2. Wrist flexion-extension for Subject 1: distribution of joint angles frequencies, and distribution*
 243 *of cutting force, wrist flexion and extension torque and effort depending on wrist flexion and extension*
 244 *angles*

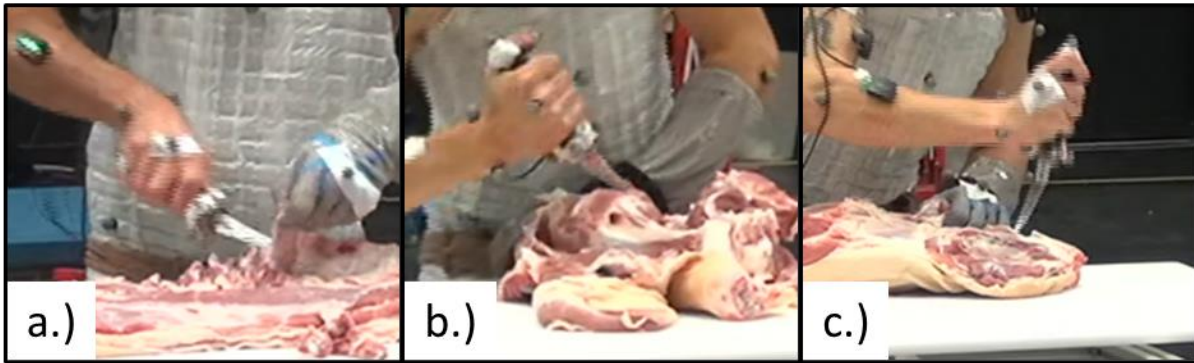


245

246 *Figure 3. Wrist radio-ulnar deviation for Subject 1: distribution of joint angles frequencies, and*
 247 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 248 *ulnar angles*

249

250 Based on the sustainability analysis used in this study, the work cycle of only Subject 4 was sustainable
 251 in all exertion directions, as RR_c was less than RA_c . For the remaining five subjects, RR_c
 252 exceeded RA_c in two exertion directions (Table 3). Wrist extension was the only direction for which
 253 RR_c never exceeded RA_c . Subjects 1, 2 and 3 had RR_c exceeding in radial deviation, while Subjects 5
 254 and 6 had RR_c exceeding in ulnar deviation.



255

256 *Figure 4. Knife grips used during the experiments: a.) forward knife grip; b.) edge-in reverse knife grip*
 257 *(cutting edge inwards) ; c.) edge-out reverse knife grip (cutting edge outwards).*

258 *Tass1* indicates if any exertion in the work cycle had $EqEff_i$ that exceeded the MAE_i for its
 259 corresponding DC_i (Table 3). For three subjects (Subjects 3, 5 and 6), there was at least one and
 260 maximum three exertions where the $EqEff_i$ that exceeded the MAE_i , on a total of 27 exertions per
 261 cycle on average (See Supplementary Material). The mean of the peak assistive torque required to
 262 reduce the $EqEff_i$ to MAE_i across the repetitions of the subjects was at most 1.6Nm. Naturally,
 263 subjects requiring *Tass1* required *Tass2* as well to make the work cycle sustainable in the
 264 corresponding exertion directions. 50% (1.1Nm) reduction in wrist flexion effort (torque) was needed
 265 for Subject 5. While 56% (5.6Nm) reduction in ulnar and radial deviation effort (torque) was needed
 266 for Subject 5 and 3, respectively.

267 The work cycle can be unsustainable even if individual exertions are sustainable as seen in the case of
 268 Subjects 1 and 2 performing PB. They do not require *Tass1* but require up to 60% (5.8Nm) reduction
 269 in wrist flexion effort (torque) and up to 40% (2.2Nm) reduction in radial deviation effort (torque) to
 270 make the work cycle sustainable. Subjects 3 and 6 also required *Tass2* in wrist flexion while not
 271 requiring *Tass1*. In wrist extension, Subject 6 required *Tass2* in only one repetition, resulting in mean
 272 RR_c lower than RA_c . Likewise, in ulnar deviation Subjects 2 and 3 required *Tass2* in one and two
 273 repetitions, respectively, resulting in mean RR_c lower than RA_c . Table 3

274

275 Table 3. Rest available in the work cycle RA_C , rest required RR_C , assistive torques τ required computed
 276 in Tass1 (T1) and Tass2 (T2) (Nm), decrease δ in current effort value required computed in Tass2 (%):
 277 individual results, mean μ and standard deviation (SD)

278

	(s)	Flexion				Extension				Ulnar Deviation				Radial Deviation			
		(s)	(Nm)	(Nm)	(%)	(s)	(Nm)	(Nm)	(%)	(s)	(Nm)	(Nm)	(%)	(s)	(Nm)	(Nm)	(%)
S ₁	22	10.8	0.0	4.2	56	1	0.0	0.0	0	3	0.0	0.0	0	56	0.0	2.2	40
SD	3	39	0.0	1.3	13	1	0.0	0.0	0	1	0.0	0.0	0	6	0.0	0.4	10
S ₂	25	13.6	0.0	5.8	60	0	0.0	0.0	0	14	0.0	0.2	3	57	0.0	2.1	37
SD	6	39	0.0	1.6	12	0	0.0	0.0	0	13	0.0	0.4	7	18	0.0	1.5	22
S ₃	8	26	0.0	4.0	47	0	0.0	0.0	0	8	0.0	0.4	5	63	1.1	5.6	56
SD	1	4	0.0	1.0	10	0	0.0	0.0	0	1	0.0	0.5	6	17	0.7	1.0	7
S ₄	17	5	0.0	0.0	0	6	0.0	0.0	0	9	0.0	0.0	0	6	0.0	0.0	0
SD	2	1	0.0	0.0	0	1	0.0	0.0	0	1	0.0	0.0	0	2	0.0	0.0	0
S ₅	30	32.1	1.1	5.4	50	3	0.0	0.0	0	44.1	1.6	5.6	56	3	0.0	0.0	0
SD	4	22.5	0.9	1.4	9	6	0.0	0.0	0	10.5	0.4	0.3	6	5	0.0	0.0	0

S 6	40	12 7	0.0	3.1	36	30	0.0	0.1	2	55 9	0.7	5.0	53	7	0.0	0.0	0
S D	4	40	0.0	1.2	10	16	0.0	0.2	4	19 6	0.5	0.7	7	4	0.0	0.0	0

279 Yellow cells: assistance required.

280 4. DISCUSSION

281 The aim of this exploratory study was to propose an extensive biomechanical characterization of meat
282 cutting tasks performed by a reduced set of professional butchers, to estimate the need for assistance
283 and, when required, to provide data on the direction and level of assistance needed at the wrist. The
284 global assessment of the tasks showed that every professional butcher but one exceeded the
285 biomechanical sustainability threshold described by Potvin (2012) and Gibson & Potvin (2016).
286 Comprehensive kinematic and kinetic data with professional butchers performing real meat cutting
287 tasks were collected for this study. Joint angle values often exceeded recommendations (*NF ISO*
288 *11228-3*, 2007), especially in wrist extension (45°) and ulnar deviation (20°). Capturing the kinematics
289 of the knife was also critical to understand the difference in knife grips and its consequences for the
290 joint torques required at the wrist. For example, this study showed that for PSR, Subject 4 had a
291 sustainable work cycle while Subject 3 had an unsustainable work cycle. This can be due to the specific
292 strategy of Subject 4. Subject 4 used three different knife grips enabling him to obtain a fairly even
293 split in duration of exertion between the exertion directions, unlike Subject 3, who used two knife
294 grips. Moreover, the additional change in knife grip for Subject 4 resulted in greater CT and RA_c
295 compared to Subject 3, leading to a lower frequency of exertions in the work cycle. These factors
296 favorably affected the sustainability analysis for Subject 4. Given the limited subjects in this study, a
297 future study with more subjects should investigate in detail if switching knife grips could be a viable
298 strategy to reduce the risk of MSDs.

299 Raw value of forces also exceeded recommendations stated in the RULA ergonomics tool assessment
300 (McAtamney & Nigel Corlett, 1993), as peak and average forces always exceeded the first threshold

301 of 20N for repeated loads and for Subject 2, the peak force exceeded the second threshold (100N).
302 This is consistent with epidemiological studies that display correlations between physical load and
303 MSDs incidence or prevalence in the meat cutting industry (Frost et al., 1998; Gorsche et al., 1998;
304 Moore & Garg, 1994; Nordander et al., 2009). In addition, peak and average cutting moments of
305 16.2Nm and 4.0Nm, respectively, have been reported for pork shoulder deboning tasks (Dempsey &
306 McGorry, 2004). The cutting moments at the handle core approximately translated into peak and
307 average cutting force of 75N and 19N, respectively, considering blade length of 15cm and half handle
308 length of 6.5cm (Dempsey & McGorry, 2004; R. W. McGorry, 2001). These values compare well with
309 the values reported in the current study. The consistency of epidemiological and biomechanical
310 literature with our study legitimates the use of assistance to reduce the physical workload, though the
311 number of tasks and subjects investigated was low in our study. Thus, the direction, then the level of
312 assistance that could be proposed based on our results will be discussed consecutively.

313 **4.1 Directions to be assisted**

314 In our study, wrist flexion torques were excessive compared to subject individual capabilities for
315 almost every subject, ulnar deviation or radial deviation torques were excessive depending on
316 subjects, and extension torques were considered sustainable for every subject. The differences in
317 torque and assistance requirement between radio-ulnar deviation can be associated with changes in
318 cutting strategy or knife grip for different tasks. PB, performed by Subjects 1 and 2 with the forward
319 knife grip, were over-represented in radial deviation while PS, performed by Subjects 5 and 6 with
320 predominantly the edge-in reverse knife grip, were over-represented in ulnar deviation. Thus, our
321 results suggest that assistive devices must be able to adjust to task and/or subject specific
322 requirements to be efficient. In addition, high inter-subject (or inter-task) variability was found for
323 every parameter measured or computed in our study, which was expected in meat cutting tasks
324 (Chander et al., 2022; Dempsey & McGorry, 2004; Silvin, 1999). Moreover, only three tasks were
325 investigated in the study, while a range of different tasks is usually performed in a meat processing

326 plant, and each task was performed by two subjects specialized in this specific task. To further evaluate
327 the results of the study, the consistency of our data with the MSDs encountered in the meat cutting
328 industry are discussed.

329 The epidemiologic literature highlights carpal tunnel syndrome, trigger finger syndromes (Frost et al.,
330 1998; Gorsche et al., 1998) and non-specific hand/wrist pain (Moore & Garg, 1994) as the most
331 prevalent distal upper limb MSDs in the meat cutting industry. Forceful exertions, especially when
332 combined with repetitive movement or awkward posture of hand or fingers, are considered a risk
333 factor for carpal tunnel syndrome (Keir et al., 2021). Trigger finger syndromes are due to finger flexor
334 tendons tenosynovitis (Durand et al., 2011), finger flexors being involved both in fingers and wrist
335 flexion (Marieb, 1993). Consequently, the excessive wrist flexion exertions highlighted in our study
336 seem consistent with the high prevalence of carpal tunnel and trigger finger syndromes in butchers,
337 although such results should be confirmed on a larger cohort of subjects. Also, the sustainable
338 exertions in wrist extension highlighted in our study seems consistent with the epidemiologic
339 literature, as e.g. finger extensors MSDs are not highlighted in epidemiologic studies performed in the
340 meat processing industry (Frost et al., 1998; Gorsche et al., 1998; Moore & Garg, 1994). Elbow
341 tendonitis are common among butchers (Moore & Garg, 1994), but no details about the medial versus
342 radial elbow tendonitis were found in the literature. Additionally, radial and ulnar deviations are both
343 controlled by several muscles, inserted on both lateral and medial epicondylitis, like finger extensors
344 and flexor carpi radialis for radial deviation and flexor and extensor carpi ulnaris for ulnar deviation.
345 Thus, literature does not give indication regarding the relative importance of a radial or ulnar deviation
346 torque assistance and cannot help prioritizing between assistance for radial or ulnar deviation.

347 Consequently, wrist flexion and possibly radio-ulnar deviation seem the more relevant directions to
348 be assisted during meat cutting tasks. As overrepresentation across time of wrist flexion was always
349 associated with overrepresented ulnar deviation, and wrist extension with radial deviation, a coupled
350 functional motion can be suspected. This coupled motion, known as a “dart-throwing motion” of the

351 wrist, has been demonstrated to be the most common wrist motion in activities of daily living
352 (Moritomo et al., 2007). This raises the question of the need to assist the wrist proportionally in
353 coupled degrees of freedom. In addition, maximal torques were developed in different wrist positions,
354 depending on the subject (see Figure 2A and Figure 3A for Subject 1). Consequently, assistance should
355 be provided on the largest possible articular amplitude in flexion/extension.

356 **4.2 Level of assistance**

357 Assistive torque requirements were computed in two ways. T_{ass1} (Table 3) identified exertions that
358 were highly stressful due to large effort requirement for the DC_i of the exertion. RR_c and T_{ass2}
359 (Table 3) served to understand the overall sustainability of the work cycle. Meat cutting is a highly
360 dynamic activity with cutting exertions often consisting of several cutting strokes, resulting in peaks
361 and dips in the computed effort. The sustainability analysis showed more instances of T_{ass2}
362 requirement than T_{ass1} requirement, indicating that the fast-paced and repetitive nature of meat
363 cutting tasks is a problem that affected subjects more than isolated exertions with large force/torque
364 requirements. There can be several ways to address the problem. With T_{ass2} , we adapted a strategy
365 of uniform reduction in the effort required in the work cycle to achieve sustainability while
366 maintaining the same cycle time. With T_{ass1} , we targeted specific exertions and made them
367 sustainable in isolation, without considering the sustainability of the overall cycle, which explains why
368 T_{ass1} is much lower than T_{ass2} . T_{ass1} and T_{ass2} can potentially be used to determine the
369 specifications of an assistive device, however the data must be extended with more subjects. While
370 Subjects 1 and 2, performing PB, showed similar reduction in effort in the corresponding exertion
371 directions, subject pairs for PSR and PS showed some inconsistencies in the level of assistance
372 required.

373 TAV envelopes (Xia & Law, 2015) were implemented in the MAE models, defining the joint strengths.
374 The MAE model accounted more or less for torques, repetitiveness, joint angles, and velocity in a
375 single indicator, the three first factors being major factors of MSDs (NF ISO 11228-3, 2007). The choice

376 in this study was to measure isometric joint strengths, making *TAV* envelopes specific instead of using
377 some of the literature. It was indeed expected that butchers will be stronger in wrist strength
378 compared to literature data. This was true for all but Subjects 5 and 6 in radial deviation strength
379 (Chander et al., 2022; Xia & Law, 2015). Thus, the results in this study must be carefully considered
380 when applying to new butchers, whose wrist strength may not still be conditioned by their work.
381 McGorry et al. (2000) found that experienced butchers spent less time applying torque than less
382 experienced butchers and suggested that using more power and less time allowed experienced
383 butchers a greater recovery period or conditioning at job allowed them to sustain higher exertion
384 levels than less experienced butchers. Based on the *MAE* model, sustainability can be achieved by
385 reducing effort or increasing recovery period, or a combination of both. It is also certain that an
386 increase in joint strength of experienced butchers due to job conditioning will reduce the effort
387 exerted in all the exertions and, consequently, result in a reduction in RR for the task. Moreover, as
388 seen in this study, change of knife grip during meat cutting tasks might also be a strategy that could
389 be employed to improve the sustainability of the task. The *MAE* model, with subject specific joint
390 strength, can indeed be used to investigate the strategies used by experienced butchers in a future
391 study.

392 However, joint strength implemented in *MAE* models are only estimations, as many factors are known
393 to modify them (Nuzzo et al., 2019). For example, neither the influence of interactions between the
394 different degrees of freedom on wrist joint strength (La Delfa & Potvin, 2017), nor the influence of
395 remote joint angles like elbow and shoulder (Delp et al., 1996; Xia & Law, 2015, Haering et al. 2017)
396 could be estimated by available models. Both issues are encountered in the tasks, as flexion-extension
397 and radio-ulnar deviations are performed during meat cutting, i.e. with or without shoulder abduction.
398 Additionally, joint torques estimated are net joint torques. Thus, muscle co-contraction is not
399 accounted for during the tasks, even if co-contraction is necessary to ensure a given level of
400 performance during the execution of the task. This is an approximation (Latash, 2018), which can
401 underestimate the assessment of MSDs risk. On the opposite, we also assumed that the muscles were

402 activated to provide an exertion torque in a given direction. However, the same joint torque can be
403 provided by different muscles over time, with adaptive changes in muscle recruitment patterns in case
404 of fatigue (Blangsted et al., 2005) in real working conditions. Thus, RR_c might be overestimated in our
405 study. These two conflicting issues may ask for further analyses at the muscle level e.g. by EMG, to
406 gain an in-depth understanding of the motor adaptations associated with performing meat cutting
407 tasks over a long period of time and better assess their sustainability.

408

409

410

411 **4.3 Limitations**

412 Limitations due to the low number of subjects involved in the study and assistive torque computation
413 have been previously discussed. Nevertheless, we can emphasize that the individual differences
414 associated with this small cohort may have a significant effect on the results, particularly as a result of
415 the healthy worker effect (Li and Sung, 1999). Limitations due to the conditions of measurement also
416 exist. The study was performed in a laboratory, where working conditions substantially differ from
417 those encountered in industry. For example, butchers usually work in a cold, noisy environment at a
418 sustained pace (Silvin, 1999), all these factors being identified as risk factors for MSDs (*NF ISO 11228-*
419 *3, 2007*). Conversely, specific constraints exist in a laboratory, like extra equipment and procedures
420 for data collection. Furthermore, our study focused on exertions at the wrist, as distal MSDs are the
421 most common (Nordander et al., 2009), but assessment of other exertions could also be of interest.
422 For example, using a hand tool like a knife involves finger flexors exertion (Marieb, 1993) and is a
423 known risk factor for MSDs in butchers (Claudon & Guiguet, 2003; Gorsche et al., 1998).
424 Measurements related to the gripping force (Gorsche et al., 1998) might be of interest, though
425 technical possibilities of assisting gripping do not seem easy to implement (Mayer et al. 2022), due to
426 the changes in knife gripping type in a single meat cutting task (Claudon & Guiguet, 2003). The physical

427 workload at the shoulder should also be assessed while evaluating an assisting device, as MSDs are
428 also common at shoulder (Nordander et al., 2009). More generally, MSDs are multifactorial diseases
429 (Bernard et al., 1997; Gouvernement du Canada, 2022; *NF ISO 11228-3*, 2007). In consequence, the
430 assistance of joint torques must be mixed with other factors to be acceptable as an ergonomic
431 approach.

432 Finally, sustainability thresholds should be considered with caution. It has to be noticed that the *MAE*
433 method, specifically developed to characterize the onset of upper limb fatigue (Potvin, 2012), is only
434 one of the various methods for globally assessing the physical risks of MSDs appearance. The choice
435 among these methods has been proven to influence the risk level estimation in some situations
436 (Antonucci, 2019). This choice is still in discussion within the scientific community (ACGIH, 2016;
437 Moore & Garg, 1995; Occhipinti & Colombini, 2007). However, in a recent study challenging different
438 criteria for rest requirement assessment, this model was found to require shorter duty cycle times and
439 lighter loads to be sustainable (Neumann et al., 2020).

440 **5. CONCLUSION**

441 This work proposed an extensive characterization of biomechanical requirements for a reduced set of
442 professional butchers, and computed the sustainability and assistive torque requirements in case of
443 the potential use of an exoskeleton at the wrist. Five of six subjects in this study exerted predominantly
444 in wrist flexion, resulting in an unsustainable workload. The exertions in radio-ulnar deviations
445 depended on the task and possibly on knife grip used by the subjects. Peak assistive torque values
446 were around 5.6 - 5.8Nm in wrist flexion, ulnar deviation, and radial deviation. However, an ideal
447 exoskeleton design should enable adjustable assistance to suit the requirements of different tasks,
448 even if practical issues may enforce the design to be focused on the most unsustainable subtasks to
449 be efficient on the largest population. The sustainability analysis showed that the fast pace of the meat
450 cutting tasks affected subjects more than isolated stressful exertions. Future work should extend the
451 sustainability analysis to more subjects and tasks, potentially also investigating subject-specific

452 strategies for the same task. In addition, the other degrees of freedom of the upper limb recorded
453 during this experimentation should be investigated in a similar manner to give a more complete view
454 of the biomechanical requirements of meat cutting.

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462 **REFERENCES**

- 463 Abdel-Malek, D. M., Foley, R. C. A., Wakeely, F., Graham, J. D., & La Delfa, N. J. (2020). Exploring
464 Localized Muscle Fatigue Responses at Current Upper-Extremity Ergonomics Threshold Limit
465 Values. *Human Factors*, 18720820940536.
- 466 ACGIH. (2016). Upper limb localized fatigue : TLV® physical agents 7th edition documentation. *The*
467 *American Conference of Governmental Industrial Hygienists*.
- 468 Antonucci, A. (2019). Comparative analysis of three methods of risk assessment for repetitive
469 movements of the upper limbs : OCRA index, ACGIH(TLV), and strain index. *International*
470 *Journal of Industrial Ergonomics*, 70, 9-21.
- 471 Arvidsson, I., Balogh, I., Hansson, G.-Å., Ohlsson, K., Akesson, I., & Nordander, C. (2012).
472 Rationalization in meat cutting—Consequences on physical workload. *Applied Ergonomics*,
473 43(6), 1026-1032.

474 Bernard, B. P., Putz-Anderson, V., & Burt, S. (1997). *Musculoskeletal disorders and workplace factors :*
475 *A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the*
476 *neck, upper extremity, and low back.*

477 Blangsted, A. K., Sjøgaard, G., Madeleine, P., Olsen, H. B., & Sjøgaard, K. (2005). Voluntary low-force
478 contraction elicits prolonged low-frequency fatigue and changes in surface electromyography
479 and mechanomyography. *Journal of Electromyography and Kinesiology: Official Journal of the*
480 *International Society of Electrophysiological Kinesiology*, 15(2), 138-148.

481 Chander, D. S., Marie, S., Gréau, M., & Pontonnier, C. (2022). Biomechanical requirements of meat
482 cutting tasks : An overview. *Comput. Methods Biomech. Biomed. Eng.*, 25(S1), 1-3.

483 Claudon, L., & Guiguet, C. (2003). Analyse de la tenue en main des couteaux lors d'opérations de
484 désossement dans différents secteurs de la filière viande. *Le travail humain*, 66(4), 377-390.

485 de Kok, J., Vroonhof, P., Snijders, J., Roullis, G., Clarke, M., Peereboom, K., van Dorst, P., & Isusi, I.
486 (2019). *Work-related musculoskeletal disorders : Prevalence, costs and demographics in the*
487 *EU | Safety and health at work EU-OSHA*. European Agency for Safety and Health at Work (EU-
488 OSHA). [https://osha.europa.eu/fr/publications/work-related-musculoskeletal-disorders-](https://osha.europa.eu/fr/publications/work-related-musculoskeletal-disorders-prevalence-costs-and-demographics-eu/view)
489 [prevalence-costs-and-demographics-eu/view](https://osha.europa.eu/fr/publications/work-related-musculoskeletal-disorders-prevalence-costs-and-demographics-eu/view)

490 Delp, S. L., Grierson, A. E., & Buchanan, T. S. (1996). Maximum isometric moments generated by the
491 wrist muscles in flexion-extension and radial-ulnar deviation. *Journal of Biomechanics*, 29(10),
492 1371-1375.

493 Dempsey, P. G., & McGorry, R. W. (2004). Investigation of a Pork Shoulder Deboning Operation.
494 *Journal of Occupational and Environmental Hygiene*, 1(3), 167-172.

495 Durand, S., Daunois, O., Gaujoux, G., Méo, S., Sassoon, D., & Strubé, F. (2011). [Trigger digits]. *Chirurgie*
496 *De La Main*, 30(1), 1-10.

497 Frost, P., Andersen, J. H., & Nielsen, V. K. (1998). Occurrence of carpal tunnel syndrome among
498 slaughterhouse workers. *Scandinavian Journal of Work, Environment & Health*, 24(4),
499 285-292.

500 Gibson, M., & Potvin, J. R. (2016, October). An equation to calculate the recommended cumulative rest
501 allowance across multiple subtasks. In *Association of Canadian Ergonomists (ACE)*
502 *Conference, Niagara Falls, ON.*

503 Gibson, M., & Potvin, J. (2017). *Calculating the Maximum Acceptable Effort for an Isolated Subtask*
504 *While Still Accounting for the Demands of all Other Subtasks.*

505 Haering, D., Pontonnier, C., Bideau, N., Nicolas, G., & Dumont, G. (2019). Using Torque-Angle and
506 Torque–Velocity Models to Characterize Elbow Mechanical Function: Modeling and Applied
507 Aspects. *Journal of Biomechanical Engineering*, 141(8).

508 Gorsche, R., Wiley, J. P., Renger, R., Brant, R., Gemer, T. Y., & Sasyniuk, T. M. (1998). Prevalence and
509 incidence of stenosing flexor tenosynovitis (trigger finger) in a meat-packing plant. *Journal of*
510 *Occupational and Environmental Medicine*, 40(6), 556-560.

511 Gouvernement du Canada, C. canadien d'hygiène et de sécurité au travail. (2022, février 1). *Troubles*
512 *musculo-squelettiques liés au travail - Facteurs de risque : Réponses SST.*
513 <https://www.cchst.ca/oshanswers/ergonomics/risk.html>

514 Karasek, R., Baker, D., Marxer, F., Ahlbom, A., & Theorell, T. (1981). Job decision latitude, job demands,
515 and cardiovascular disease : A prospective study of Swedish men. *American Journal of Public*
516 *Health*, 71(7), 694-705.

517 Karlton, J., Vogel, K., Bergstrand, M., Eklund, J. (2016) Maintaining knife sharpness in industrial meat
518 cutting: A matter of knife or meat cutter ability, *Applied Ergonomics*, 56, 92-100

519 Keir, P. J., Farias Zuniga, A., Mulla, D. M., & Somasundram, K. G. (2021). Relationships and Mechanisms
520 Between Occupational Risk Factors and Distal Upper Extremity Disorders. *Human Factors*,
521 63(1), 5-31.

522 La Delfa, N. J., & Potvin, J. R. (2017). A musculoskeletal model to estimate the relative changes in wrist
523 strength due to interacting wrist and forearm postures. *Computer Methods in Biomechanics*
524 *and Biomedical Engineering*, 20(13), 1403-1411.

525 Latash, M. L. (2018). Muscle coactivation : Definitions, mechanisms, and functions. *Journal of*
526 *Neurophysiology*, 120(1), 88-104.

527 Lemerle, B., & Chicot, B. (2018). *Observatoire des troubles musculo-squelettiques des actifs agricoles :*
528 *Bilan national 2012-2016* (N° 12030). Caisse centrale MSA.

529 Li, C. Y., & Sung, F. C. (1999). A review of the healthy worker effect in occupational epidemiology.
530 *Occupational medicine*, 49(4), 225-229.

531 Maithani, H., Corrales Ramon, J. A., Lequievre, L., Mezouar, Y., & Alric, M. (2021). Exoscarne : Assistive
532 strategies for an industrial meat cutting system based on physical human-robot interaction.
533 *Applied Sciences*, 11(9), 3907.

534 Marieb, E. N. (1993). *Anatomie et physiologie humaines* (2e éd). De Boeck université.

535 Marsot, J., Claudon, L., & Jacqmin, M. (2007). Assessment of knife sharpness by means of a cutting
536 force measuring system. *Applied Ergonomics*, 38(1), 83-89.

537 Mayer, T. A., Harsch, A. K., Koska, D., Hensel-Unger, R., & Maiwald, C. (2022). Effects of an active
538 hand exoskeleton on forearm muscle activity in industrial assembly grips. *Work*, 72(4), 1577-
539 1591.

540 McAtamney, L., & Nigel Corlett, E. (1993). RULA : A survey method for the investigation of work-
541 related upper limb disorders. *Applied Ergonomics*, 24(2), 91-99.

542 McGorry, R., L. Young, S., Murphy, P., & Brogmus, G. (2000). Experimental appraisal of a manual task
543 evaluator. *International Journal of Industrial Ergonomics*, 25(3), 265-274.

544 McGorry, R. W. (2001). A system for the measurement of grip forces and applied moments during
545 hand tool use. *Applied Ergonomics*, 32(3), 271-279.

546 McGorry, R. W., Dempsey, P. G., & O'Brien, N. V. (2004). The effect of workstation and task variables
547 on forces applied during simulated meat cutting. *Ergonomics*, 47(15), 1640-1656.

548 Moore, J. S., & Garg, A. (1994). Upper extremity disorders in a pork processing plant : Relationships
549 between job risk factors and morbidity. *American Industrial Hygiene Association Journal*,
550 55(8), 703-715.

551 Moore, J. S., & Garg, A. (1995). The Strain Index : A proposed method to analyze jobs for risk of distal
552 upper extremity disorders. *American Industrial Hygiene Association Journal*, 56(5), 443-458.

553 Moritomo, H., Apergis, E. P., Herzberg, G., Werner, F. W., Wolfe, S. W., & Garcia-Elias, M. (2007). 2007
554 IFSSH Committee Report of Wrist Biomechanics Committee : Biomechanics of the So-Called
555 Dart-Throwing Motion of the Wrist. *The Journal of Hand Surgery*, 32(9), 1447-1453.

556 Muller, A., Pontonnier, C., Puchaud, P., & Dumont, G. (2019). CusToM : A Matlab toolbox for
557 musculoskeletal simulation. *The Journal of Open Source Software*, 4(33), 1-3.

558 Neumann, W. P., Motiwala, M., & Rose, L. M. (2020). A comparison of work-rest models using a
559 “breakpoint” analysis raises questions. *IIE Transactions on Occupational Ergonomics and*
560 *Human Factors*, 8(4), 187-194

561 *NF ISO 11228-3*. (2007, novembre). Afnor EDITIONS.

562 Nordander, C., Ohlsson, K., Akesson, I., Arvidsson, I., Balogh, I., Hansson, G.-A., Strömberg, U., Rittner,
563 R., & Skerfving, S. (2009). Risk of musculoskeletal disorders among females and males in
564 repetitive/constrained work. *Ergonomics*, 52(10), 1226-1239.

565 Nuzzo, J. L., Taylor, J. L., & Gandevia, S. C. (2019). CORP : Measurement of upper and lower limb muscle
566 strength and voluntary activation. *Journal of Applied Physiology*, 126(3), 513-543.

567 Occhipinti, E., & Colombini, D. (2007). Updating reference values and predictive models of the OCRA
568 method in the risk assessment of work-related musculoskeletal disorders of the upper limbs.
569 *Ergonomics*, 50(11), 1727-1739.

570 Pontonnier, C., De Zee, M., Samani, A., Dumont, G., & Madeleine, P. (2014). Strengths and limitations
571 of a musculoskeletal model for an analysis of simulated meat cutting tasks. *Applied ergonomics*,
572 45(3), 592-600.

573 Pontonnier, C., Dumont, G., de Zee, M., Samani, A., & Madeleine, P. (2012). Cutting Force and EMG
574 Recordings for Ergonomics Assessment of Meat Cutting Tasks : Influence of the Workbench
575 Height and the Cutting Direction on Muscle Activation Levels. *Volume 4: Advanced*

576 *Manufacturing Processes; Biomedical Engineering; Multiscale Mechanics of Biological Tissues;*
577 *Sciences, Engineering and Education; Multiphysics; Emerging Technologies for Inspection.*

578 Pontonnier, C., Marie, S., Chander, D., Kirchhofer, S., & Gréau, M. (2021). Evaluating the action
579 detection of an active exoskeleton : A muscle-control synchronicity approach for meat cutting
580 assistance. *Computer Methods in Biomechanics and Biomedical Engineering.*

581 Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks : An equation based on
582 duty cycle. *Human Factors, 54(2), 175-188.*

583 Puchaud, P., Sauret, C., Muller, A., Bideau, N., Dumont, G., Pillet, H., & Pontonnier, C. (2020). Accuracy
584 and kinematics consistency of marker-based scaling approaches on a lower limb model : A
585 comparative study with imagery data. *Computer Methods in Biomechanics and Biomedical*
586 *Engineering, 23(3), 114-125.*

587 Savescu, A., Cuny-Guerrier, A., Wild, P., Reno, G., Aublet-Cuvelier, A., Claudon, L. (2018) Objective
588 assessment of knife sharpness over a working day cutting meat, *Applied Ergonomics, 68(4),*
589 *109-116.*

590 Silvin, S. (1999). *Sollicitations biomécaniques des opérateurs dans les ateliers de découpe de viande*
591 *[Thèse d'exercice]. Université de Nancy I.*

592 Tappin, D. C., Bentley, T. A., & Vitalis, A. (2008). The role of contextual factors for musculoskeletal
593 disorders in the New Zealand meat processing industry. *Ergonomics, 51(10), 1576-1593.*

594 Tirloni, A. S., Dos Reis, D. C., Tirloni, S. F., & Moro, A. R. P. (2020). Exertion Perception When
595 Performing Cutting Tasks in Poultry Slaughterhouses : Risk Assessment of Developing
596 Musculoskeletal Disorders. *International Journal of Environmental Research and Public*
597 *Health, 17(24), 9534.*

598 Tirloni SF, Tirloni AS, Roqueiro N, Díaz Merino EA, Schmidt Alves Díaz Merino G, Moro A.R.P.
599 (2021). Cutting force measurement: Hand tool instrumentation used in slaughterhouses - a
600 systematic review. *EXCLI J. 2021 Apr 13;20:727-747.*

601 Tomezzoli, A., Schuster, A., Dumont, G., & Pontonnier, C. (2023). *Effect of mass addition on upper limb*
602 *joint torques during meat cutting tasks : A parametric study*. 48th Congres of the Société de
603 Biomecanique (2023)., Grenoble.

604 Villalobos, A., Mac Cawley, A. (2022) Prediction of slaughterhouse workers' RULA scores and knife
605 edge using low-cost inertial measurement sensor units and machine learning algorithms,
606 *Applied Ergonomics*,98(1),103556

607 Wu, G., van der Helm, F. C. T., Veeger, H. E. J. D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J.,
608 Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., Buchholz, B., & International Society of
609 Biomechanics. (2005). ISB recommendation on definitions of joint coordinate systems of
610 various joints for the reporting of human joint motion--Part II : Shoulder, elbow, wrist and
611 hand. *Journal of Biomechanics*, 38(5), 981-992.

612 Xia, T., & Law, L. (2015). Wrist joint torque-angle-velocity performance capacity envelope evaluation
613 and modelling. *International Journal of Human Factors Modelling and Simulation*, 5(1), 33-52.

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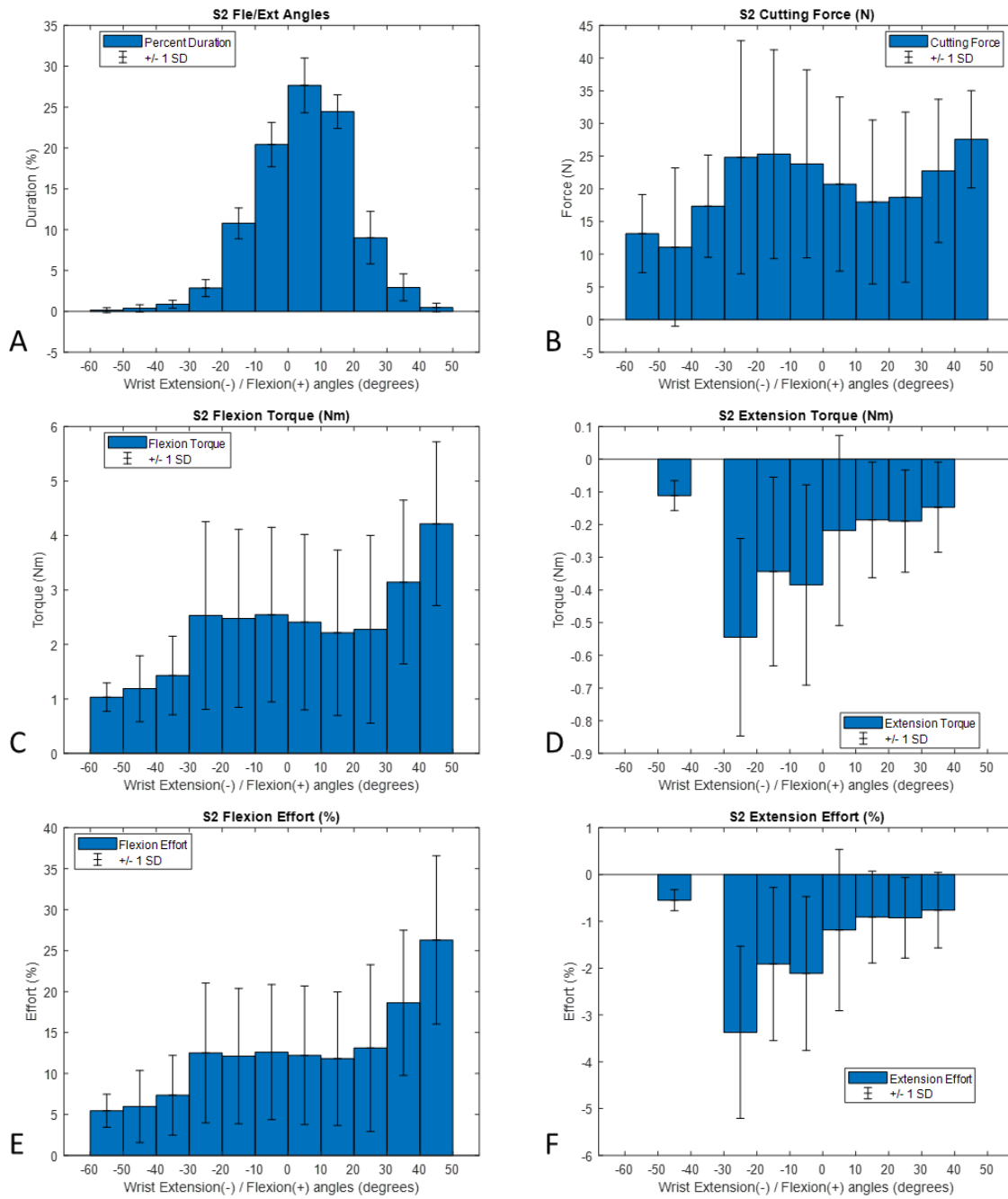
SUPPLEMENTARY MATERIAL

632 The data presented in the following pages correspond the descriptive representation of the
633 biomechanical quantities investigated during the task for each subject individually. For sake of
634 concision, only subject 1 was presented in the article. The first table summarizes general information
635 about the cutting task for each subject.

636 *Table 1: Cutting task summary parameters: Cycle time, number of exertions, frequency of*
637 *exertions, average and peak cutting force and moment. Mean (+/- SD)*

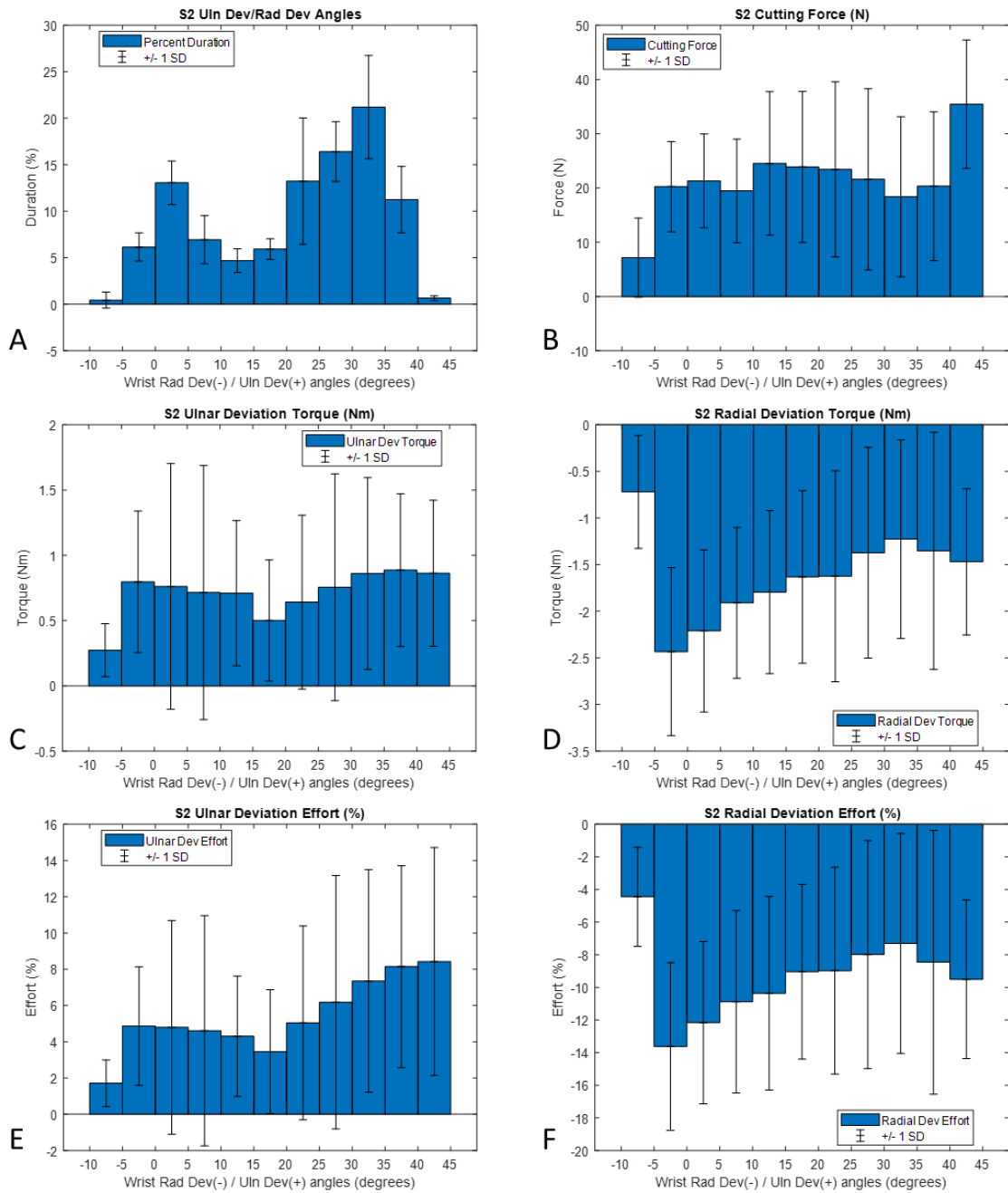
Subject	CT (s)	Number of exertions	Frequency of exertions (/min)	Cutting Force (N)		Cutting Moment (Nm)	
				Average	Peak	Average	Peak
S1	53 (-)	28 (1)	31.4 (0.7)	24.2 (3.2)	79.9 (10.8)	1.2 (0.1)	5.0 (1.4)
S2	71 (-)	42 (3)	35.2 (2.9)	21.0 (2.1)	104.7 (11.0)	1.0 (0.0)	4.2 (0.6)
S3	21 (-)	14 (3)	38.4 (8.2)	23.7 (0.8)	58.1 (5.4)	1.4 (0.1)	5.1 (0.4)
S4	31 (-)	13 (3)	24.8 (5.0)	20.5 (3.8)	57.7 (7.0)	1.4 (0.2)	4.5 (0.5)
S5	52 (-)	28 (4)	31.6 (4.1)	29.9 (1.5)	90.8 (3.2)	1.8 (0.1)	5.1 (0.4)
S6	75 (-)	40 (8)	32.2 (6.6)	21.5 (2.5)	67.8 (9.3)	1.6 (0.1)	5.9 (0.4)

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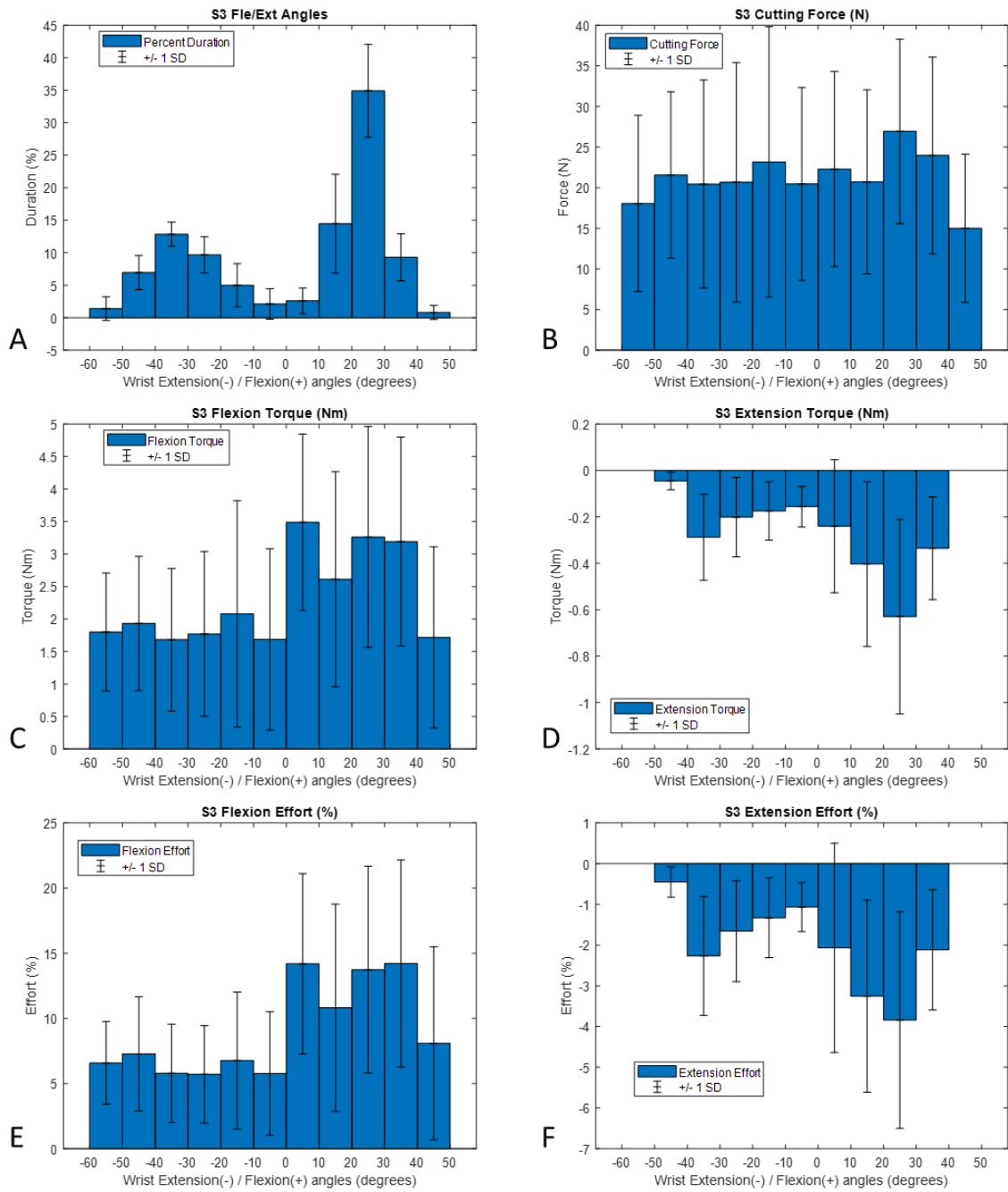
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640 *Figure 1. Wrist flexion-extension for Subject2: distribution of joint angles frequencies, and*
 641 *distribution of cutting force, wrist flexion and extension torque and effort depending on wrist flexion*
 642 *and extension angles*



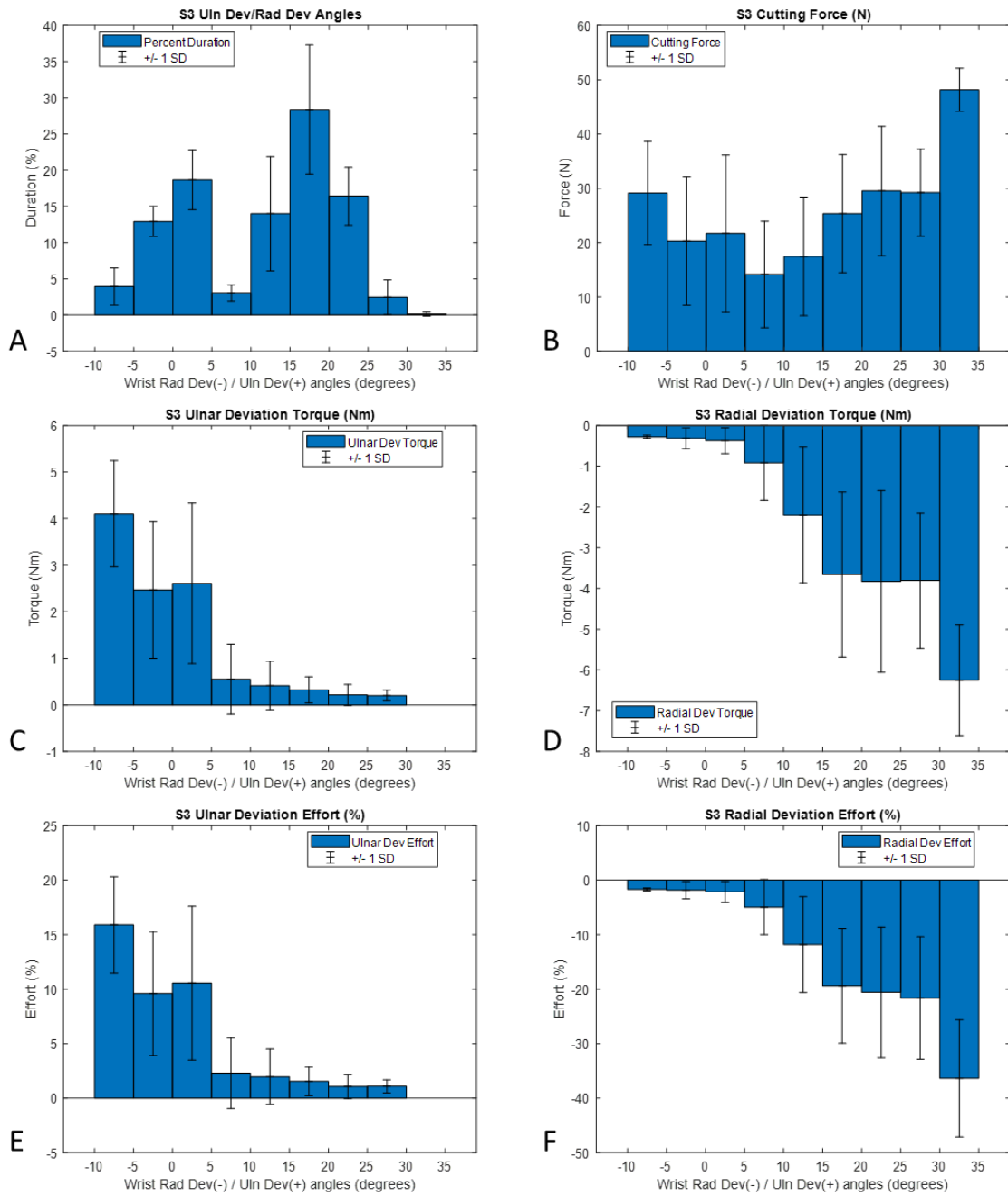
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644 *Figure 2. Wrist radio-ulnar deviation for Subject 2: distribution of joint angles frequencies, and*
 645 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 646 *ulnar angles*



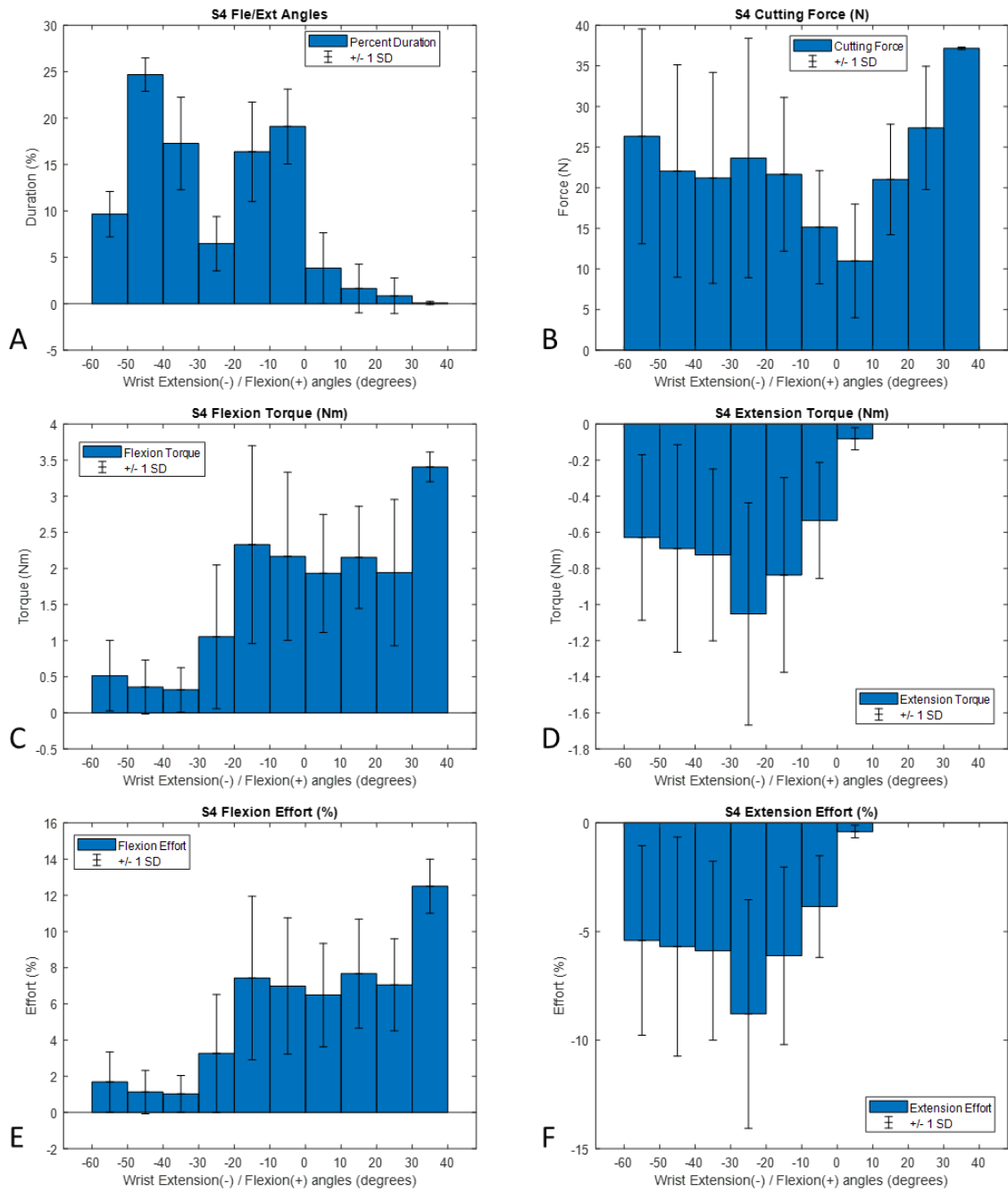
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648 *Figure 3. Wrist flexion-extension for Subject3: distribution of joint angles frequencies, and*
 649 *distribution of cutting force, wrist flexion and extension torque and effort depending on wrist flexion*
 650 *and extension angles*



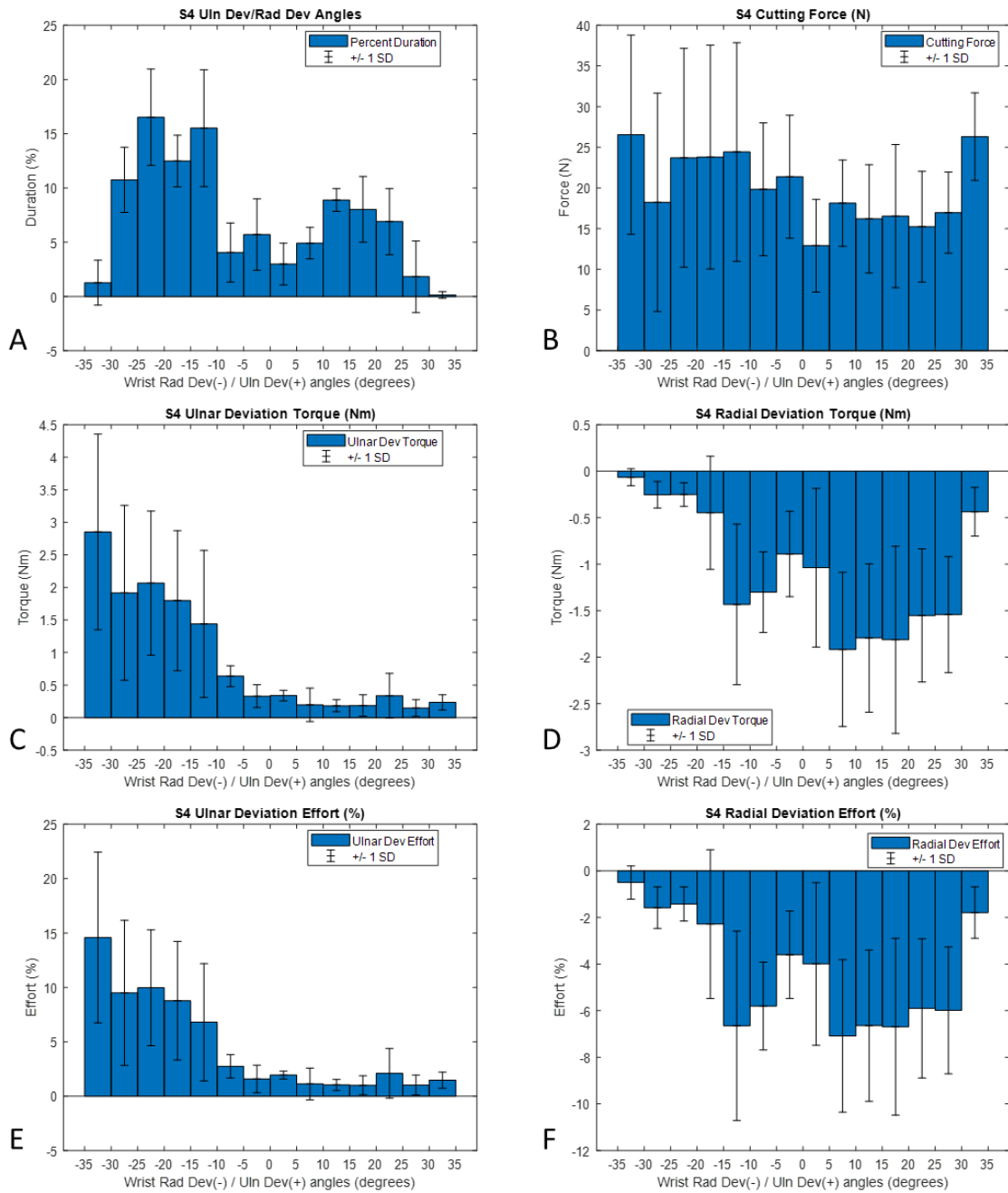
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652 *Figure 3. Wrist radio-ulnar deviation for Subject3: distribution of joint angles frequencies, and*
 653 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 654 *ulnar angles*



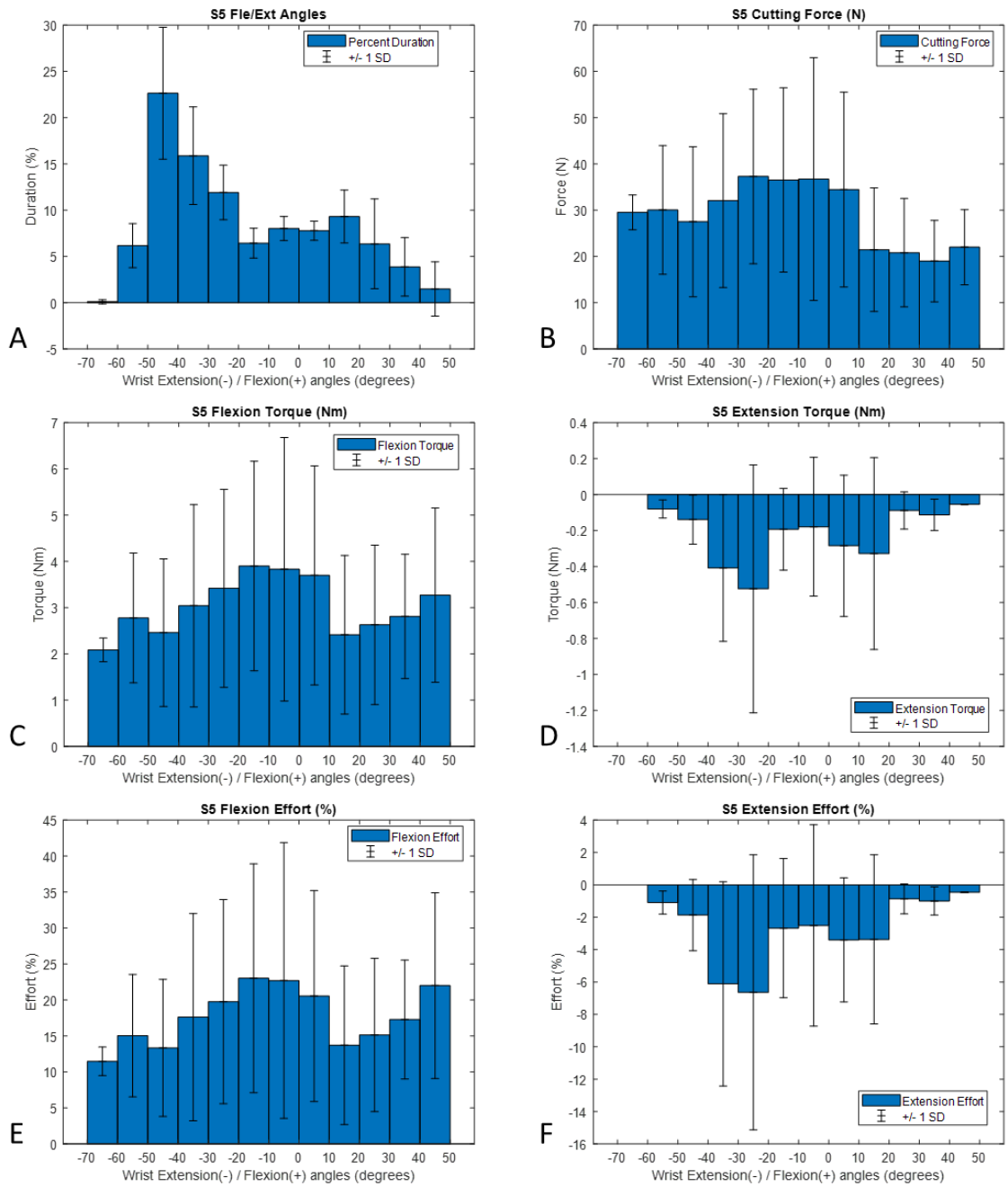
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656 *Figure 4. Wrist flexion-extension for Subject4: distribution of joint angles frequencies, and*
 657 *distribution of cutting force, wrist flexion and extension torque and effort depending on wrist flexion*
 658 *and extension angles*



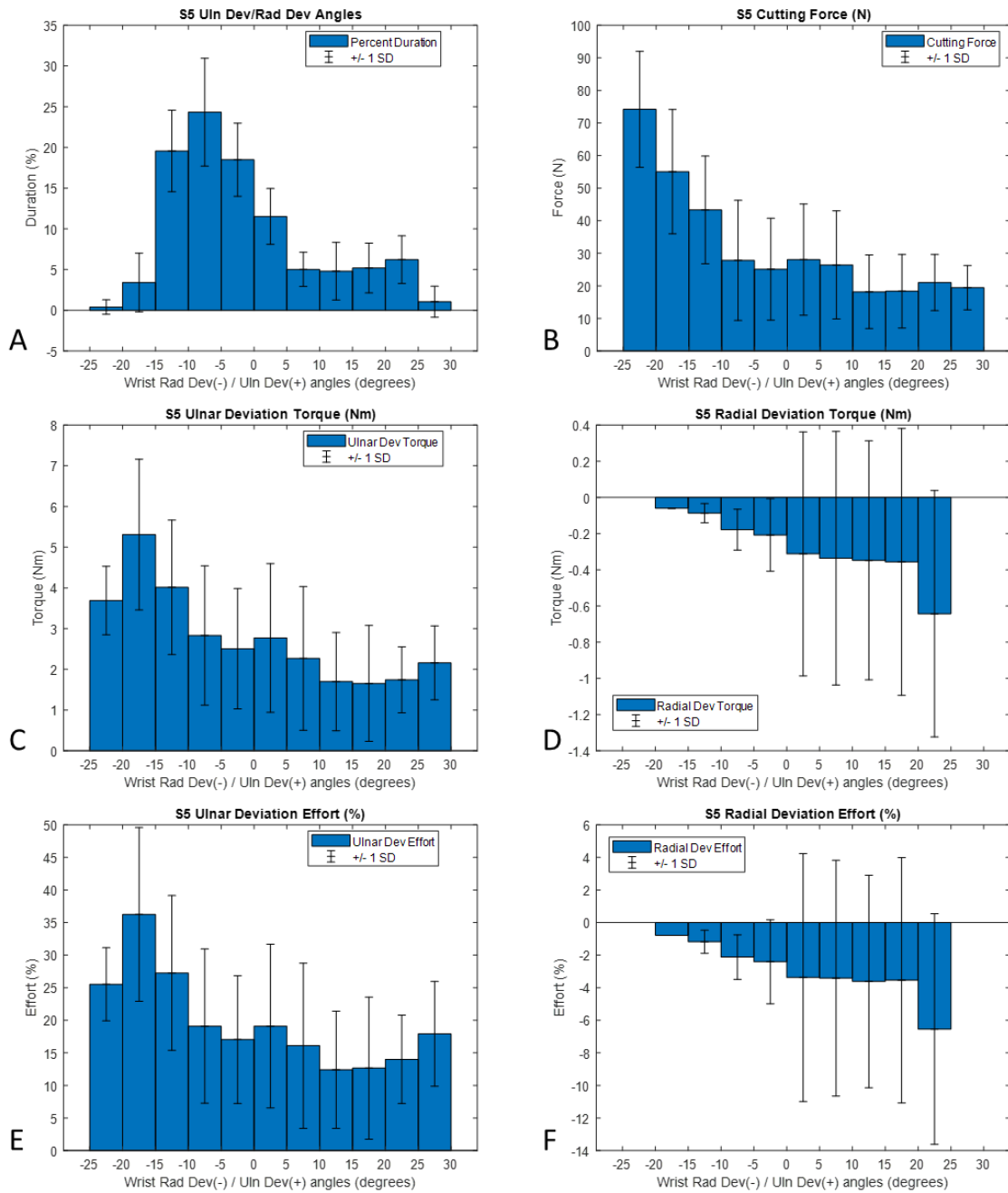
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660 *Figure 5. Wrist radio-ulnar deviation for Subject1: distribution of joint angles frequencies, and*
 661 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 662 *ulnar angles*



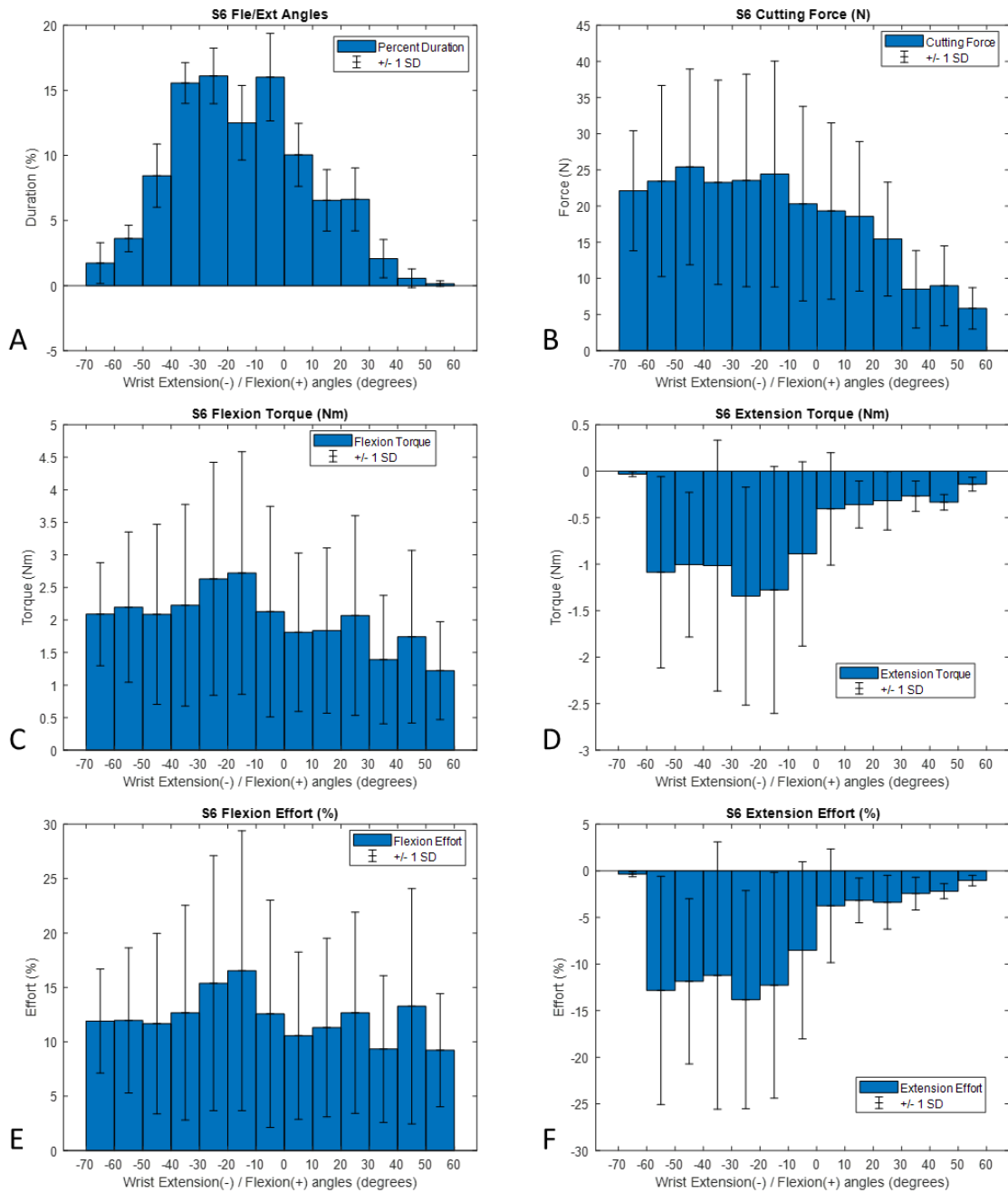
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664 *Figure 6. Wrist flexion-extension for Subject5: distribution of joint angles frequencies, and*
 665 *distribution of cutting force, wrist flexion and extension torque and effort depending on wrist flexion*
 666 *and extension angles*



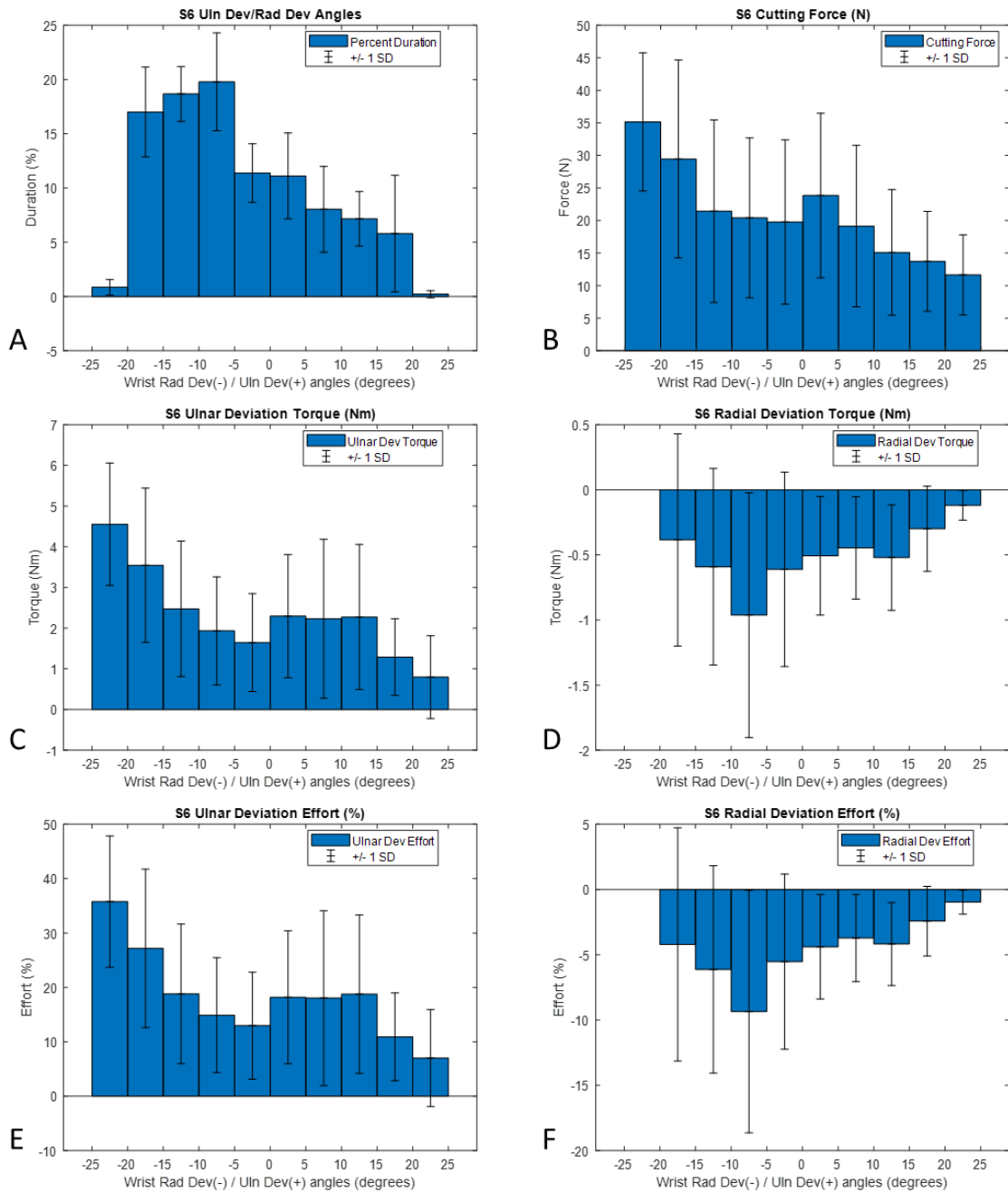
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668 *Figure 7. Wrist radio-ulnar deviation for Subject5: distribution of joint angles frequencies, and*
 669 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 670 *ulnar angles*



671

672 *Figure 8. Wrist flexion-extension for Subject6: distribution of joint angles frequencies, and*
 673 *distribution of cutting force, wrist flexion and extension torque and effort depending on wrist flexion*
 674 *and extension angles*



675

676 *Figure 9. Wrist radio-ulnar deviation for Subject6: distribution of joint angles frequencies, and*
 677 *distribution of cutting force, wrist radial and ulnar torque and effort depending on wrist radial and*
 678 *ulnar angles*

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