



HAL
open science

Effects of pace on productivity and physical and mental workloads in a Human-Cobot Collaboration

Kévin Bouillet, Sophie Lemonnier, Fabien Clanché, Gérome C Gauchard

► To cite this version:

Kévin Bouillet, Sophie Lemonnier, Fabien Clanché, Gérome C Gauchard. Effects of pace on productivity and physical and mental workloads in a Human-Cobot Collaboration. *International Journal of Occupational Safety and Ergonomics*, 2025, 31 (1), pp.328-336. <10.1080/10803548.2024.2440265>. <hal-04890246>

HAL Id: hal-04890246

<https://hal.univ-lorraine.fr/hal-04890246v1>

Submitted on 16 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC0 1.0 - Universal - International License

1 **Effects of pace on productivity and physical and mental workloads in a**
2 **Human-Cobot Collaboration**

3 K. Bouillet^{ab*}, S. Lemonnier^{cd}, F. Clanche^e and G. Gauchard^{abe}

4 *^aUR 3450 DevAH, University of Lorraine, Vandoeuvre-lès-Nancy, France; ^bCare*
5 *Grand Est, University of Lorraine, Nancy, France; ^cEA 7312 PErSEUs, University of*
6 *Lorraine, Metz, France; ^dUniversity of Lorraine, CNRS, Inria, LORIA, F-54000 Nancy,*
7 *France, ^eFaculty of Sport Sciences, University of Lorraine, Villers-lès-Nancy, France*

8 * Email: kevin.bouillet@univ-lorraine.fr

9 K. Bouillet: 0000-0001-8819-8995

10 S. Lemonnier: 0000-0002-9650-7054

11 F. Clanche: 0000-0001-5164-7398

12 G. Gauchard: 0000-0002-2489-9343

13 **Funding**

14 This work was supported by the Lorraine University of Excellence (15-IDEX-0004)
15 project C-SHIFT.

16

17 **Declaration of interest statement**

18 The authors report there are no competing interests to declare.

19

20 **Acknowledgements**

21 We are grateful to the AIP Lorrain, in particular to its director Muriel Lombard for
22 having welcomed us in its premises. We also thank all participants for their involvement
23 in this study.

24

25 **Effects of pace on productivity and physical and mental workloads in a** 26 **Human-Cobot Collaboration**

27 **Abstract:**

28 Introduction: Musculoskeletal disorders (MSDs) represent a prevalent
29 global occupational health concern, primarily associated with high biomechanical
30 solicitations, mental workload, and work pace. Although cobots have shown
31 promise in reducing risks of MSDs, a question of interest still persists as to how
32 the effect of pace in hybrid human-machine collaboration will affect the operator,
33 in terms of both physical and cognitive health and the production.

34 Methods: This study aimed to analyse the impact of pace on productivity,
35 operators' posture and mental workload in a human-cobot collaboration.
36 Involving twenty participants engaged in a collaborative task with a cobot under
37 three cobot-led paces, the study assessed productivity RULA scores (posture),
38 dual task performance (cognitive resources) and NASA-TLX (workload).

39 Results: The findings revealed that an excessively high pace had
40 counterproductive effects, leading to reduced efficiency and increased
41 susceptibility to MSDs, both in terms of physical and mental workloads.

42 Conclusion: Therefore, in the context of a human-cobot collaboration, it
43 is imperative to adapt the pace to operators' abilities in order to ensure optimal
44 productivity while preserving their health, emphasizing the need for a balanced
45 approach to pace management in such collaborative work scenarios.

46 **Keywords:** human-cobot collaboration; pace; productivity; posture;
47 musculoskeletal disorders; workload

48

49 **1. Introduction**

50 Musculoskeletal disorders (MSDs) are the prevailing occupational diseases worldwide,
51 affecting individuals and businesses significantly [1,2]. Predominantly, the upper limb
52 joints and the back are the regions most commonly impacted by MSDs. A dynamic
53 model by the French National Research and Safety Institute (*INRS*) outlined the
54 multifactorial nature of MSD development involving various factors [3].

55 Biomechanical constraints, particularly awkward postures, repetitive tasks, and
56 applied force, collectively elevate the risk of developing MSDs [4,5]. These factors do
57 not impact the musculoskeletal system independently but interactively. Proper
58 assessment of MSD risk must consider the combined effects of posture, force, and pace,
59 as well as the similarity of repetitive movements, which further increases the risk. The
60 posture of the upper limbs and the force applied during tasks are interconnected [6,7]
61 and should be evaluated together to accurately measure the load and associated risk.

62 Posture with the shoulder forward at 45°, elbow at 90°, and neutral positions of
63 the wrist and forearm allows optimal force production, considering the set of 12
64 different postures [6], matching with low scores for these joints in RULA evaluations
65 [8]. Awkward postures correspond to deviations from these postures, requiring
66 additional energy to compensate for the loss of force [9], increasing risks of MSDs. The
67 biomechanical solicitations could be influenced by some task parameters as the working
68 height, depth of work area or workpiece weight, which could influence force and
69 posture of the operators. Moreover, the frequency of performing repetitive tasks
70 intensifies the biomechanical constraints, especially in awkward postures, further
71 increasing the risk of MSDs [10,11]. For example, a fast work pace is identified as a
72 contributing factor that heightens the odds of developing MSDs [12,13].

73 Nevertheless, biomechanical constraints are not the sole contributors to MSDs.
74 The INRS dynamic model highlights that factors like workstation rotation, overtime,
75 and work pace significantly influence biomechanical load. Workstation rotation reduces
76 movement similarity, lowering risk, while overtime and increased work pace elevate
77 biomechanical stress. These factors, combined with biomechanical constraints, jointly
78 impact the overall risk of developing MSDs. Moreover, the risks could be influenced by

79 psychosocial aspects (e.g., mental workload, psychological demands, meaning of work
80 [14]), stress [3,15], and individual parameters as gender or experience for example [16].

81 Preventing MSDs is crucial since once an operator experiences these disorders,
82 it is already too late. Various assessment tools are available to evaluate the risk of
83 MSDs. For posture assessment, methods such as OWAS [17], OCRA [18], REBA [19],
84 and RULA [8] are commonly used. In the literature RULA method is the most used
85 [20,21], assessing repetitive task with light weight. To assess mental workload,
86 objective tools like pupillometry [22], electroencephalography [23], heart rate [24] or
87 dual-task paradigm [25–27] and subjective measures like NASA-TLX [28,29] are
88 commonly employed. By utilizing both objective and subjective measures, a
89 comprehensive understanding of the operator's mental workload can be attained.
90 Moreover, integrating both physical and mental assessments provides a comprehensive
91 understanding of the potential risks of MSDs, facilitating interventions to manage and
92 mitigate these risks.

93 In the age of Industry 4.0, collaborative robots, or cobots, enable high levels of
94 interactions with a human worker: performing complex tasks within the same
95 workspace, including the possibility of physical contact [30]. Introducing a cobot into a
96 task inevitably modifies the dynamics between the operator and their work, influencing
97 performance, motor activity, safety and health [31]. The introduction of a cobot aims to
98 maximize productivity while minimizing human workload [32].

99 Recent studies have examined the impact of integrating cobots into work
100 situations, focusing on productivity and operator posture. Firstly, comparisons between
101 individual work scenarios and collaborative scenarios involving a human and a cobot
102 have shown that the introduction of a cobot brings benefits in terms of productivity and

103 operator posture [33,34] and mental workload with a decrease in perceived workload,
104 assessed by NASA-TLX, and errors during the assembly process [35].

105 On the other hand, a recent study compared a human system (i.e., two humans)
106 with a hybrid system (i.e., one human and one cobot) in a collaborative work situation
107 [36]. The findings indicated that the hybrid system exhibited decreased productivity
108 compared to the human system, attributed to compromised interactions between the two
109 workers and a heightened mental workload within the hybrid system. Nevertheless,
110 participants in the hybrid system demonstrated a lower risk of developing MSDs based
111 on their posture. A parallel study shared similar outcomes when comparing a hybrid
112 system with a human system [37]. In this context, the question of the work pace could
113 be raised. Indeed, in order to gain a better understanding of the factors involved in
114 preventing MSDs, it would seem necessary to know whether it is the presence of the
115 cobot or the reduction in work pace when working with the cobot that is responsible for
116 the reduction in biomechanical constraints.

117 The pace could play an important role in both productivity and operators' health.
118 In our knowledge, there is a lack of A heightened pace increases the number of gestures
119 and reduces the available time to complete them. Consequently, time pressure
120 intensifies with a shrinking time window. Time pressure is defined as "a psychological
121 feeling and emotional experience when time is limited and it is generated when people
122 deal with limited time" [38,p.600]. Schreuder and Mioch [39] distinguished pressure
123 time when task time exceed 70% and high pressure time when exceeding 85% of
124 available time. Time pressure and production efficiency are related. Saptari et al. [40]
125 showed that a 10% reduction in time cycle heightened time pressure, leading to more
126 errors despite increased productivity. Moreover, physical workload may escalate due to
127 a higher number of gestures and a diminution in idle periods.

128 There is a gap in understanding how the increased work pace affect human
129 health parameters in human-robot interactions. Therefore, this study aimed to
130 investigate the impacts of pace within a collaborative work environment involving a
131 human and a cobot. The objective was to analyse how varying pace levels influences
132 production performance and operator posture and mental workload with the hypothesis
133 that increasing the pace in a human-cobot collaboration is expected to result in higher
134 productivity and an elevated risk of MSDs due to a riskier posture and amplified
135 attentional load and perceived workload.

136

137 **2. Materials and methods**

138 ***2.1. Participants***

139 Twenty volunteers from the University of Lorraine, with an average age of 21.2 ± 2.0
140 years (11 men and 9 women; 18 right-handed and 2 left-handed), participated in this
141 study. The number of participants was determined using an a priori power analysis with
142 G*Power 3.1.9.7, based on an effect-size of $f = 0.3$, an α error probability of 0.05, and a
143 power ($1 - \beta$ error probability) of 0.8. These twenty participants did not participate to
144 the previous study [36]. So, they had not any prior experience in the collaborative task
145 and in working with a cobot. None of the participants had motor control or attentional
146 behaviour impairments, avoiding participants to complete tasks simultaneously. This
147 study was approved by the Ethics Committee Sud Méditerranée under reference 2021-
148 A00471-40, and prior to their participation, all individuals provided written consent.

149

150 **2.2. Collaborative hybrid task**

151 The participants engaged in a collaborative task with a YuMi cobot from ABB Group
152 (Zürich, Switzerland), equipped with two arms featuring seven points of articulation and
153 two clips at the end of each arm, along with a vacuum on its left "wrist" (Figure 1A).

154 The task involved the manufacturing of products comprising a fairing, an
155 aluminium product (SFP product, which stands for Flexible Production System, for
156 *Système Flexible de Production* in French), a cover, three nuts, and three screws (Figure
157 1B). The subtasks were predefined with a precise order. Participants completed four
158 steps to manufacture these products, which included inserting the aluminium product
159 into the fairing, introducing the nut into the fairing, and then screwing the products
160 three times. The cobot co-worker moved the fairing, moved the cover on the product-in-
161 progress, rotated the product-in-progress twice between participants screwing, and
162 evacuated the finished product at the end. The manufacturing process took place on a
163 collaborative working plan (Figure 1A). This working plan was heighted between 5 and
164 10 centimetres under the participant's elbow height as recommended [41]. The finished
165 products weight was 140g, so products and their components were light to avoid any
166 muscular fatigue for participants.

167 Participants performed this collaborative hybrid task under three conditions,
168 according to the imposed-pace led by the cobot. An intermediate MEAN condition was
169 established based on a very similar prior experimental study [36], where the same
170 collaborative task was performed, but participants could set their own pace (while
171 aiming to work as fast as possible). In the MEAN condition, participants were instructed
172 to produce four products within three minutes. SLOW and FAST conditions were then
173 defined, with respectively three and five products to manufacture within the same three-
174 minutes timeframe. In the three conditions, the speed of cobot's arm was similar

175 between the three conditions, only the predefined time between its subtasks was
176 changed between conditions (9, 5 and 3 seconds respectively for SLOW, MEAN and
177 FAST).

178 After each trial, the experimenter verified the quality of the products
179 manufactured. If any step was not completed, it was disregarded, and the product was
180 considered wasted. The number of manufactured products and the number of steps
181 performed were measured for each trial. The percentage of products and steps achieved,
182 relative to the expected numbers, was then calculated. These four variables allowed to
183 analyse the performance at the collaborative task.

184

185 ***2.3. Kinematics and RULA evaluations***

186 Participants were equipped with seventeen motion capture sensors, namely 60Hz
187 wireless inertial units MVN BIOMECH Awinda (Xsens, Enschede, The Netherlands),
188 distributed across their head, trunk, upper limbs, and lower limbs [42]. These sensors
189 provided position coordinates and orientation data for various body segments.
190 Subsequently, joint angles for the back, neck, shoulders, elbows, and wrists were
191 computed using Xsens MVN Animate Pro 2021.0.0 software's biomechanical model
192 and a MATLAB program.

193 RULA evaluations were performed for each frame of a trial based on the joint
194 angles, measured with motion capture sensors, considering the upper limb with trunk
195 and neck and the left upper limb with trunk and neck [8]. An overall RULA score was
196 then calculated, with a MATLAB program, for both the left and right sides, averaging
197 all the RULA scores throughout the whole trial. The overall RULA score ranges from 1
198 to 7, where a higher score indicates an elevated risk of developing MSDs, emphasizing

199 the need to adjust the operator's posture [8]. The RULA scores for the joints (i.e.,
200 shoulders, elbows, wrists, neck and back) were also calculated throughout the whole
201 trial. The percentage of time spent within the values 3 to 6 was computed.
202 Subsequently, the time spent in scores 3 and 4 was added, as the scores 5 and 6, to
203 calculate the time spent in the risk levels 2 and 3, respectively, as defined by
204 McAtamney and Corlett [8].

205 Therefore, for participants' posture, overall RULA scores and RULA scores for
206 all joints were compared between conditions, as the time spent in risks level 2 and 3 of
207 RULA evaluations.

208

209 ***2.4. Mental workload: attentional demand and subjective workload***

210 Alongside the collaborative task, participants took part in an auditory task inspired by
211 Richer and Lajoie [43], resembling the auditory task in Bouillet et al. [36]. During this
212 task, participants listened to an audio recording containing random presentations of
213 letters (B, D, P, and T) with a two-second inter-stimulus interval. The letters were pre-
214 recorded by a speech language therapist, and the recordings were generated using a
215 MATLAB program. Subsequently, participants were required to announce the number
216 of occurrences of a specific predetermined letter in the recording once it concluded. The
217 absolute error, measuring the discrepancy between the participant's response and the
218 correct answer, was then calculated.

219 Additionally, to assess the subjective workload, participants completed the
220 French-translated version of the NASA-TLX questionnaire [28], adapted by Cegarra
221 and Morgado [44]. The NASA-TLX comprised six questions, each representing a
222 dimension of workload, including mental demand, physical demand, temporal demand,

223 effort, performance, and frustration. Both the overall NASA-TLX score and the scores
224 for each individual dimension were used to evaluate the subjective workload
225 experienced by the participants. The NASA-TLX score ranges from 0 to 100 and
226 NASA-TLX scores for each dimension vary from 0 to 33. A higher score indicates a
227 higher perceived workload.

228 Therefore, the mental workload was measured by the absolute error at the
229 auditory task, the global NASA-TLX score and the NASA-TLX score for each
230 dimension.

231

232 ***2.5. Process***

233 Participants completed all conditions, with each condition comprising one block of
234 three trials lasting for three minutes each. To mitigate learning or fatigue effects, the
235 order of the blocks was counterbalanced: either in a crescendo sequence (SLOW,
236 MEAN and FAST) or a decrescendo sequence (FAST, MEAN and SLOW).

237 Before the trials, participants received detailed explanations about the materials
238 and tasks. They also read an information document about the experiment and signed a
239 consent form. Following this, motion capture sensors were fitted on their bodies, and
240 they completed the calibration process for the motion capture system [42].

241 Participants underwent four learning phases of three minutes each: a
242 collaborative task as single task leading at a free-pace (participants led the pace to
243 familiarize to the task and interaction with the cobot co-worker); an auditory task as a
244 single task; both tasks while leading at a free-pace at the collaborative task; both tasks
245 in the MEAN condition. Subsequently, participants completed all the trials, with short
246 breaks of two to three minutes between trials to reset the working plan, and longer

247 breaks of five to six minutes between each condition, during which they filled out the
248 NASA-TLX questionnaire.

249

250 *2.6. Statistical analyses*

251 For all variables (excluding NASA-TLX scores, see Table 1), the average value was
252 computed for each condition (SLOW, MEAN and FAST) based on the data from the
253 three trials conducted by participants. Any outliers (data points falling three standard
254 deviations below or above the mean) were replaced with the median value of the
255 respective condition [45]. Due to issues with motion capture sensors data were observed
256 for one participant (sternum sensor moved and distorted data), this participant was
257 excluded for posture analysis.

258 A non-parametric Friedman's repeated measures ANOVA was employed to
259 compare the three conditions for all variables. In cases where the test yielded significant
260 results, three paired-samples Wilcoxon tests were conducted to further compare the
261 three conditions.

262 The results are presented as median values along with the interquartile range for
263 each condition. All statistical analyses were conducted using STATISTICA v.10
264 software. The level of significance α was set at 0.05.

265 Detailed results (mean of the trials of each variable for conditions of each
266 participant) are available on Open Science Framework:

267 https://osf.io/84asz/?view_only=7543537abade445fa90508cbc24c330c

268

269 **3. Results**

270 ***3.1. Collaborative task performances***

271 The number and percentage of products manufactured and steps performed showed
272 significant differences among the conditions ($p < 0.001$ for all variables).

273 The number of products manufactured (Figure 2A) was lower in SLOW
274 compared to MEAN ($p < 0.001$) and FAST ($p < 0.05$), with no significant difference
275 between MEAN and FAST. Conversely, the number of steps (Table 2) was the lowest
276 in SLOW and the highest in FAST ($p < 0.001$ for all comparisons).

277 The percentage of products manufactured and steps performed differed
278 according to the conditions ($p < 0.001$, Figure 2B and Table 2). The highest percentage
279 of products manufactured was observed in SLOW ($p < 0.01$ compared to MEAN and p
280 < 0.001 compared to FAST), whereas the slowest was seen in FAST ($p < 0.05$
281 compared to MEAN). Similar comparisons were found for the percentage of steps
282 performed ($p < 0.01$ between MEAN and both other conditions, and $p < 0.001$ between
283 SLOW and FAST).

284

285 ***3.2. Kinematics and RULA evaluations***

286 Regarding the RULA overall scores, values differed according to the conditions for both
287 sides ($p < 0.01$), with higher RULA overall scores in FAST compared to SLOW ($p <$
288 0.05) and MEAN ($p < 0.01$). No significant differences were observed between SLOW
289 and MEAN for both sides. The RULA overall scores for a trial for both sides are
290 presented in Table 3. The RULA scores for all joints and the differences are shown in
291 Appendix 1.

292 The time spent in level risks 2 and 3 of RULA evaluation differed between
293 conditions for the left side ($p < 0.01$), with more time spent in level risk 2 in SLOW
294 than in MEAN ($p < 0.01$) and FAST ($p < 0.001$) and less time spent in level risk 3 in
295 SLOW than in MEAN ($p < 0.05$) and FAST ($p < 0.001$). No differences were shown for
296 the time spent in level risks 2 and 3 of RULA evaluation for the right side. The time
297 spent in level risks 2 and 3 of RULA evaluation for both sides are presented in Table 3.
298

299 ***3.3. Mental workload: attentional demand and subjective workload***

300 The absolute error in the auditory task differed according to the conditions ($p < 0.01$,
301 Figure 3A), with the lowest value observed in SLOW ($p < 0.05$ compared to FAST and
302 $p < 0.01$ compared to MEAN). However, no significant difference was observed
303 between MEAN and FAST.

304 Regarding the NASA-TLX scores (Figure 3B), significant differences were
305 observed among the conditions ($p < 0.001$). Specifically, the scores varied based on the
306 conditions for mental demand ($p < 0.05$), temporal demand ($p < 0.001$), and effort ($p <$
307 0.001). The mean scores for the global NASA-TLX and each NASA-TLX dimension,
308 along with the significant differences, are presented in Table 4.
309

310 **4. Discussion**

311 This study aimed to evaluate the impact of different paces within a collaborative
312 work task involving a human and a cobot. The findings highlight several key outcomes
313 as the pace increased in this hybrid collaborative task: first, the productivity increased
314 with the pace up to a threshold at MEAN while the production efficiency decreased
315 when the pace increased in this hybrid collaborative task; second, the posture appeared

316 to be riskier at the highest pace, especially over the long term; third, the mental
317 workload increased with the pace in this hybrid collaborative task.

318

319 The study showed that an increase in the imposed pace led to higher productivity, up to
320 a specific threshold. Specifically, both higher paces (MEAN and FAST conditions)
321 resulted in greater productivity compared to the slower ones (SLOW condition), with no
322 significant differences between the two conditions with higher paces. However, the
323 production efficiency was lowest in the FAST condition than in the MEAN condition
324 due to increased waste, including missing screws or incomplete tasks. These findings
325 are consistent with other studies indicating an increase in errors and mistakes when
326 workers operate at excessively high paces [46–48].

327 The mean-pace (MEAN condition) was aligned with the operators' abilities of
328 workers from the earlier study [36]. The increase in pace in the study was achieved
329 experimentally by minimizing the idle time of the cobot between its tasks. This led to
330 insufficient time for each participants' action, potentially resulting in a higher
331 occurrence of errors [46]. Indeed, time pressure increased with the pace and these
332 results aligns with the findings in Saptari et al.'s study [40]. In addition, a high imposed
333 pace can negatively impact human factors, such as physical and mental workloads,
334 resulting in a higher rate of errors by operators [49,50]. This deterioration in human
335 factors, especially linked to the reduction in microbreaks, could hinder production
336 performance within the hybrid system. The difficulties in synchronizing actions with the
337 cobot, resulting from compromised human factors, could further worsen production
338 issues.

339 Comparison of overall RULA scores revealed that posture was significantly
340 riskier at the highest pace, with no difference between SLOW and MEAN conditions.

341 The increase in risks was observed in the left shoulder and back of the participants.
342 Indeed, the increase in pace mechanically led to more actions, a known contributing
343 factor to the occurrence of MSDs [10–13], even in light physical task, as the
344 collaborative task here, as underlined in the study by Ekpenyong and Inyang [13] on
345 1.200 workers.

346 Objective biomechanical load, measured here with RULA overall scores,
347 showed an increase between MEAN and FAST conditions, while subjective physical
348 load, measured with NASA-TLX scores for the physical demand, did not show any
349 difference between both conditions. These results indicated a no-perception of the
350 increase of the physical load by the participants. Cippelletti et al. (2023) [51] indicated
351 that operators could have different perceptions of the load, especially with repetitive
352 movements. The difference between objective and subjective assessments could be
353 explained by the previous experience of the worker: “state of his health, his past, his
354 personal norms and values” [52,p.8].

355 Working at a high pace can also lead to modification in the motor behaviour of
356 operators as they adapt to the new time constraints to enhance efficiently [46]. Indeed,
357 the higher pace led to adjustments in workers’ posture as they had to perform additional
358 subtasks to increase productivity. Subtask-related postures were riskier than idle-related
359 postures [36]. Thus, when the cobot reduced its idle time, human workers became more
360 active and adopted riskier postures with fewer breaks for comfort and recovery [53].
361 This reduction in microbreaks periods could also potentially result in increased
362 muscular fatigue if operators worked for extended periods.

363 The comparisons of RULA scores seemed to align with the productivity
364 threshold at which the high-pace became overly demanding for participants, exceeding
365 their human workers, leading to an increased risk of MSDs alongside a decline in

366 production efficiency.

367

368 The perceived workload was significantly influenced by the pace, with an increase in
369 pace corresponding to a rise in perceived workload, as indicated by the higher NASA-
370 TLX global scores. These elevated scores were primarily attributed to increased mental
371 and temporal demands, as well as heightened effort. Effort dimension batches physical
372 and mental demands, thus the increase shown in this experiment was linked with the
373 higher mental demand. The reduction in available time for actions during high-pace
374 conditions (i.e., 3 seconds for screwing in FAST, 5 seconds in MEAN and 9 seconds in
375 SLOW) led to greater temporal pressure, contributing to the elevated score related to
376 temporal demand [28,44]. The increase in mental demand coincided with the heightened
377 attentional demand observed in the results of the auditory task, indicating that the
378 collaborative motor task became more challenging around the mean-pace threshold
379 [54]. Consequently, with the too high-pace for the operator, the high mental workload
380 could indirectly lead to more errors by operators in the manufacturing process [55].

381 The slowest pace in this hybrid collaborative task proved to be the most efficient
382 for the operators' mental workload. However, it could potentially evoke negative
383 feelings, such as feelings of useless, boredom, frustration, or depreciation due to
384 prolonged idle periods among the operators [56], although no difference was detected in
385 the frustration dimension in the NASA-TLX here. Negative feelings might be more
386 pronounced in real-world settings involving experienced operators, whose expectations
387 of cobot use could differ from those of the study participants [57].

388 Therefore, when the pace reached its maximum in the study, surpassing the pace
389 matching with operators' abilities, both attentional demand and perceived workload
390 were the highest. Moreover, existing literature strongly links high perceived workload

391 to the risks of MSDs [58,59]. The mental workload became risky for participants when
392 operating at this excessively high pace within the collaborative task. The presence of a
393 cobot co-worker changed the mental workload of operators either by reducing it or
394 increasing it [36]. This difference could be explained by the repartition of the subtasks
395 between the participants and the co-worker. In the last study, the pace was lower with
396 the cobot co-worker than with the human co-worker. Therefore, in a collaborative
397 hybrid system, such as the one examined in this study, it is crucial to choose a pace that
398 matches the operators' abilities to prevent excessive mental workload and reduce the
399 risk of developing MSDs.

400

401 Some features on the generalization in industry could be advanced in this study, the first
402 on the degree of collaboration and the second on the experience of the participants.

403 In the assembly task of this study, the presence of a human operator is justified
404 by the need for precise screwing, while the cobot assists by alleviating the human
405 worker from constraining subtask as product rotation, as observed in previous work
406 [60]. It represents a lightweight collaborative operation, and is among the most
407 prevalent forms of hybrid collaborative task with cobots in the French industry,
408 alongside activities such as handling and sanding [61]. While the study findings may
409 not be generalized directly to all hybrid collaborative tasks, they are therefore
410 particularly relevant for lightweight assembly tasks that involve cobot collaboration.

411 NASA-TLX scores for physical demand were quite low for the three conditions.
412 For FAST condition, the quicker condition for the participants, the scores were with a
413 median of 2.3 (5.1) out of 33.3. Mental and temporal demands were superior at the
414 mean possible value (16.7) only for the FAST condition. These results appeared to
415 indicate that the collaborative task was not a very difficult one [62]. Further studies

416 could focus on the pace parameter for a more challenging task, either physically, or
417 mentally, or both.

418 The experiment involved young participants unfamiliar with manufacturing
419 tasks and cobot usage. Despite their inexperience, they adapted quickly, showing no
420 significant learning effect across phases. Indeed, the number of products manufactured
421 in FAST did not significantly differ between the group of ten participants who began
422 with this condition and the group who concluded with it. This suggests that novices can
423 perform this collaborative task effectively, implying the results may be applicable to
424 real-world settings.

425 However, the observed effects on the student population (young, not expert)
426 may not be replicated to industrial workers. Experienced workers have different gesture
427 patterns [63], strategies [64]. Moreover, a real operator has different expectations and
428 worries with the introduction of the cobot, which could lead to different behaviours for
429 the interaction [57]. Therefore, it would be beneficial to replicate this study with
430 experienced workers to validate these findings in a more representative sample of the
431 industrial workforce. Acceptability and acceptance notions could also be evaluated with
432 real operators [51,65], allowing a better understanding of the question of pace in the
433 collaborative hybrid task. This would enhance the external validity of the results and
434 provide more comprehensive guidelines for implementing cobot in industrial
435 environments.

436

437 **5. Conclusion**

438 During this collaborative task involving human participants and a cobot, the incremental
439 increase in pace initially heightened productivity. However, beyond a specific threshold

440 aligned with the operators' abilities, it resulted to diminishing productivity, decreasing
441 production efficiency, and imposed higher physical and mental workloads on the
442 operators. This, in turn, escalated the risk of health issues, particularly MSDs, as
443 operators were compelled to adopt more awkward postures while executing a greater
444 number of actions.

445 Hence, to ensure optimal productivity and human factors, it is crucial to
446 establish a pace that aligns with the abilities of both the cobot and the operators. This is
447 crucial to prevent excessive physical and mental workloads, especially considering the
448 inherent increase in operators' mental workload with the introduction of a cobot.
449 Consequently, before implementing a collaborative work scenario involving a cobot and
450 an operator, it is crucial to assess the work situation thoroughly. This includes
451 evaluating the risk of developing MSDs, considering the operator's abilities, and
452 ensuring the pace aligns with anticipated productivity while preventing MSD risks. This
453 meticulous assessment is essential for achieving optimal productivity, minimizing
454 production wastes, and safeguarding the operators' overall health.

455

456 **6. References**

- 457 [1] EU-OSHA. Work-related MSDs: prevalence, costs and demographics in the EU.
458 EU-OSHA; 2019. p. 18.
- 459 [2] L'Assurance Maladie. Rapport annuel 2021 - L'Assurance Maladie - Risques
460 professionnels. [Assurance Maladie - Occupational risks]. L'Assurance Maladie;
461 2022. p. 1–236.
- 462 [3] Uguen C, Sablon S, Carballeda G. Intégration de la préparation physique dans
463 l'approche ergonomique : quel dispositif pour quel(s) objectif(s) ? [Integrating
464 physical preparation into the ergonomic approach: which device for which
465 objective(s)?] *Activités*. 2018;15(2):1–34.
- 466 [4] Bernard BP, Putz-Anderson V. Musculoskeletal disorders and workplace factors.
467 A critical review of epidemiologic evidence for work-related musculoskeletal
468 disorders of the neck, upper extremity, and low back. [Internet]. U.S. Department

- 469 of Health and Human Services, Public Health Service, Centers for Disease
470 Control and Prevention, National Institute for Occupational Safety and Health;
471 1997 [cited 2021 Apr 23]. Report No.: 97B141. Available from:
472 <https://www.cdc.gov/niosh/docs/97-141/>.
- 473 [5] Hayes MJ, Cockrell D, Smith DR. A systematic review of musculoskeletal
474 disorders among dental professionals. *International Journal of Dental Hygiene*.
475 2009;7(3):159–165.
- 476 [6] Jain R, Meena ML, Sain MK, et al. Impact of posture and upper-limb muscle
477 activity on grip strength. *International Journal of Occupational Safety and*
478 *Ergonomics*. 2019;25(4):614–620.
- 479 [7] Roman-Liu D, Tokarski T. Upper limb strength in relation to upper limb posture.
480 *International Journal of Industrial Ergonomics*. 2005;35(1):19–31.
- 481 [8] McAtamney L, Corlett EN. RULA: a survey method for the investigation of
482 work-related upper limb disorders. *Appl Ergon*. 1993;24(2):91–99.
- 483 [9] Santos J, Baptista JS, Monteiro PRR, et al. The influence of task design on upper
484 limb muscles fatigue during low-load repetitive work: A systematic review.
485 *International Journal of Industrial Ergonomics*. 2016;52:78–91.
- 486 [10] Mathiassen SE, Winkel J. Physiological comparison of three interventions in
487 light assembly work: reduced work pace, increased break allowance and
488 shortened working days. *Int Arch Occup Environ Health*. 1996;68(2):94–108.
- 489 [11] Sundelin G. Patterns of electromyographic shoulder muscle fatigue during MTM-
490 paced repetitive arm work with and without pauses. *Int Arch Occup Environ*
491 *Health*. 1993;64(7):485–493.
- 492 [12] Ahn G, Hur S, Jung M-C. Bayesian network model to diagnose WMSDs with
493 working characteristics. *International Journal of Occupational Safety and*
494 *Ergonomics*. 2020;26(2):336–347.
- 495 [13] Ekpenyong CE, Inyang UC. Associations between worker characteristics,
496 workplace factors, and work-related musculoskeletal disorders: A cross-sectional
497 study of male construction workers in Nigeria. *International Journal of*
498 *Occupational Safety and Ergonomics*. 2014;20(3):447–462.
- 499 [14] Isaksen J. Constructing meaning despite the drudgery of repetitive work. *Journal*
500 *of Humanistic Psychology*. 2000;40(3):84–107.
- 501 [15] Bao SS, Kapellusch JM, Merryweather AS, et al. Relationships between job
502 organisational factors, biomechanical and psychosocial exposures. *Ergonomics*.
503 2016;59(2):179–194.
- 504 [16] Coutarel F, Daniellou F. L'intervention ergonomique pour la prévention des
505 troubles musculosquelettiques : quels statuts pour l'expérience et la subjectivité
506 des travailleurs ? [Ergonomic intervention for the prevention of musculoskeletal
507 disorders: what status for workers' experience and subjectivity]. *Travail et*
508 *Apprentissages*. 2011;N° 7(1):62–80.

- 509 [17] Karhu O, Härkönen R, Sorvali P, et al. Observing working postures in industry:
510 Examples of OWAS application. *Applied Ergonomics*. 1981;12(1):13–17.
- 511 [18] Colombini D. An observational method for classifying exposure to repetitive
512 movements of the upper limbs. *Ergonomics*. 1998;41(9):1261–1289.
- 513 [19] Hignett S, McAtamney L. Rapid Entire Body Assessment (REBA). *Applied*
514 *Ergonomics*. 2000;31(2):201–205.
- 515 [20] Cardoso A, Colim A, Bicho E, et al. Ergonomics and human factors as a
516 requirement to implement safer collaborative robotic workstations: A literature
517 review. *Safety*. 2021;7(4):71.
- 518 [21] Misslin Q, Grosjean J, Blandet T, et al. Ergonom.io ou l’ergonomie pour l’usine
519 du futur. [Ergonom.io or ergonomics for the factory of the future]. Saint-Malo,
520 France; 2021. p. 22.
- 521 [22] Van Acker BB, Bombeke K, Durnez W, et al. Mobile pupillometry in manual
522 assembly: A pilot study exploring the wearability and external validity of a
523 renowned mental workload lab measure. *International Journal of Industrial*
524 *Ergonomics*. 2020;75:102891.
- 525 [23] Huang L-Y, She H-C, Chou W-C, et al. Brain oscillation and connectivity during
526 a chemistry visual working memory task. *International Journal of*
527 *Psychophysiology*. 2013;90(2):172–179.
- 528 [24] Heine T, Lenis G, Reichensperger P, et al. Electrocardiographic features for the
529 measurement of drivers’ mental workload. *Applied Ergonomics*. 2017;61:31–43.
- 530 [25] Bishnoi A, Hernandez ME. Dual task walking costs in older adults with mild
531 cognitive impairment: a systematic review and meta-analysis. *Aging & Mental*
532 *Health*. 2021;25(9):1618–1629.
- 533 [26] Patel P, Lamar M, Bhatt T. Effect of type of cognitive task and walking speed on
534 cognitive-motor interference during dual-task walking. *Neuroscience*.
535 2014;260:140–148.
- 536 [27] Yang Q, Tian C, Tseng B, et al. Gait change in dual task as a behavioral marker
537 to detect mild cognitive impairment in elderly persons: A systematic review and
538 meta-analysis. *Archives of Physical Medicine and Rehabilitation*.
539 2020;101(10):1813–1821.
- 540 [28] Hart SG. Nasa-task load index (NASA-TLX); 20 years later. *Proceedings of the*
541 *human factors and ergonomics society annual meeting*. Sage. CA: Los Angeles;
542 2006. p. 904–908.
- 543 [29] Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): Results
544 of empirical and theoretical research. *Advances in Psychology* [Internet].
545 Elsevier; 1988 [cited 2022 Sep 15]. p. 139–183. Available from:
546 <https://linkinghub.elsevier.com/retrieve/pii/S0166411508623869>.

- 547 [30] Hentout A, Aouache M, Maoudj A, et al. Human–robot interaction in industrial
548 collaborative robotics: a literature review of the decade 2008–2017. *Adv Robot.*
549 2019;33(15–16):764–799.
- 550 [31] Kadir BA, Broberg O. Human well-being and system performance in the
551 transition to industry 4.0. *International Journal of Industrial Ergonomics.*
552 2020;76:102936.
- 553 [32] Pearce M, Mutlu B, Shah J, et al. Optimizing makespan and ergonomics in
554 integrating collaborative robots Into manufacturing processes. *IEEE Trans*
555 *Automat Sci Eng.* 2018;15(4):1772–1784.
- 556 [33] Colim A, Faria C, Cunha J, et al. Physical ergonomic improvement and safe
557 design of an assembly workstation through collaborative robotics. *Safety.*
558 2021;7(1):14.
- 559 [34] Gualtieri L, Palomba I, Merati FA, et al. Design of human-centered collaborative
560 assembly workstations for the improvement of operators’ physical ergonomics
561 and production efficiency: A case study. *Sustainability.* 2020;12(9):3606–3628.
- 562 [35] Gervasi R, Capponi M, Mastrogiacomo L, et al. Manual assembly and Human-
563 Robot Collaboration in repetitive assembly processes: a structural comparison
564 based on human-centered performances. *The International Journal of Advanced*
565 *Manufacturing Technology.* 2023;126:1213–1231.
- 566 [36] Bouillet K, Lemonnier S, Clanche F, et al. Does the introduction of a cobot
567 change the productivity and posture of the operators in a collaborative task?
568 *PLoS ONE.* 2023;18(8):e0289787.
- 569 [37] Mariscal MA, Ortiz Barcina S, García Herrero S, et al. Working with
570 collaborative robots and its influence on levels of working stress. *International*
571 *Journal of Computer Integrated Manufacturing.* 2023;1–20.
- 572 [38] Wang D, Shi K. The influence of reasoning capacity and time pressure on the
573 information search pattern of career decision making. 2010 IEEE 2nd
574 Symposium on Web Society [Internet]. Beijing, China: IEEE; 2010 [cited 2024
575 Jan 10]. p. 5607380. Available from:
576 <http://ieeexplore.ieee.org/document/5607380/>.
- 577 [39] Schreuder EJA, Mioch T. The effect of time pressure and task completion on the
578 occurrence of cognitive lockup. 2011.
- 579 [40] Saptari A, Jia Xin Leau, Mohamad NA. The effect of time pressure, working
580 position, component bin position and gender on human error in manual assembly
581 line. 2015 International Conference on Industrial Engineering and Operations
582 Management (IEOM) [Internet]. Dubai: IEEE; 2015 [cited 2023 Dec 19]. p. 1–6.
583 Available from: <http://ieeexplore.ieee.org/document/7093793/>.
- 584 [41] CUSSTR. Aménagement général des postes de travail [Internet]. Commission
585 Universitaire de Sécurité et santé au Travail Romande (CUSSTR); 2005 [cited
586 2020 Sep 23]. p. 27–41. Available from: <http://cusstr.ch/repository/10.pdf>.

- 587 [42] Schepers M, Giuberti M, Bellusci G. Xsens MVN: Consistent tracking of human
588 motion using inertial sensing [Internet]. 2018 [cited 2022 Jan 19]. p. 1–8.
589 Available from: [https://www.researchgate.net/profile/Martin-](https://www.researchgate.net/profile/Martin-Schepers/publication/324007368_Xsens_MVN_Consistent_Tracking_of_Human_Motion_Using_Inertial_Sensing/links/5ab8be2f0f7e9b68ef51f7ba/Xsens-MVN-Consistent-Tracking-of-Human-Motion-Using-Inertial-Sensing.pdf)
590 [Schepers/publication/324007368_Xsens_MVN_Consistent_Tracking_of_Human](https://www.researchgate.net/profile/Martin-Schepers/publication/324007368_Xsens_MVN_Consistent_Tracking_of_Human_Motion_Using_Inertial_Sensing/links/5ab8be2f0f7e9b68ef51f7ba/Xsens-MVN-Consistent-Tracking-of-Human-Motion-Using-Inertial-Sensing.pdf)
591 [_Motion_Using_Inertial_Sensing/links/5ab8be2f0f7e9b68ef51f7ba/Xsens-MVN-](https://www.researchgate.net/profile/Martin-Schepers/publication/324007368_Xsens_MVN_Consistent_Tracking_of_Human_Motion_Using_Inertial_Sensing/links/5ab8be2f0f7e9b68ef51f7ba/Xsens-MVN-Consistent-Tracking-of-Human-Motion-Using-Inertial-Sensing.pdf)
592 [Consistent-Tracking-of-Human-Motion-Using-Inertial-Sensing.pdf](https://www.researchgate.net/profile/Martin-Schepers/publication/324007368_Xsens_MVN_Consistent_Tracking_of_Human_Motion_Using_Inertial_Sensing/links/5ab8be2f0f7e9b68ef51f7ba/Xsens-MVN-Consistent-Tracking-of-Human-Motion-Using-Inertial-Sensing.pdf).
- 593 [43] Richer N, Lajoie Y. Cognitive task modality influences postural control during
594 quiet standing in healthy older adults. *Aging Clin Exp Res*. 2019;31(9):1265–
595 1270.
- 596 [44] Cegarra J, Morgado N. Étude des propriétés de la version francophone du NASA-
597 TLX. [Study of hte properties of the French version of NASA-TLX]. 5ème
598 colloque de psychologie ergonomique (Epique). Nice, France: Epique 2009;
599 2009. p. 28–30.
- 600 [45] Rustum R, Adeloye AJ. Replacing outliers and missing values from activated
601 sludge data using kohonen self-organizing map. *J Environ Eng*.
602 2007;133(9):909–916.
- 603 [46] Bosch T, Mathiassen SE, Visser B, et al. The effect of work pace on workload,
604 motor variability and fatigue during simulated light assembly work. *Ergonomics*.
605 2011;54(2):154–168.
- 606 [47] Escorpizo R, Moore A. The effects of cycle time on the physical demands of a
607 repetitive pick-and-place task. *Applied Ergonomics*. 2007;38(5):609–615.
- 608 [48] Srinivasan D, Samani A, Mathiassen SE, et al. The size and structure of arm
609 movement variability decreased with work pace in a standardised repetitive
610 precision task. *Ergonomics*. 2015;58(1):128–139.
- 611 [49] Givi ZS, Jaber MY, Neumann WP. Modelling worker reliability with learning
612 and fatigue. *Applied Mathematical Modelling*. 2015;39(17):5186–5199.
- 613 [50] Taleb I. Identification et évaluation des temps non productifs par la simulation de
614 systèmes de production pour améliorer la productivité et les conditions de travail.
615 [Identification and evaluation of non-productive time by simulating production
616 systems to improve productivity and working conditions]. [Metz, France]:
617 HESAM Université; 2022.
- 618 [51] Cippelletti E, Azouaghe S, Pellier D, et al. Assessing MSDs before introduction
619 of a cobot: Psychosocial aspects and employee’s subjective experience. *ri*
620 [Internet]. 2023 [cited 2024 Jul 5];78(1).
- 621 [52] Héraldot V. Pour une approche élargie de la pénibilité du travail. [For a borader
622 approach to the hardship of work]. *Journal des professionnels de la santé au*
623 *travail*. 2008;4:8–9.
- 624 [53] Dempsey PG, Mathiassen SE, Jackson JA, et al. Influence of three principles of
625 pacing on the temporal organisation of work during cyclic assembly and
626 disassembly tasks. *Ergonomics*. 2010;53(11):1347–1358.

- 627 [54] Lomond KV, Côté JN. Movement timing and reach to reach variability during a
628 repetitive reaching task in persons with chronic neck/shoulder pain and healthy
629 subjects. *Exp Brain Res*. 2010;206(3):271–282.
- 630 [55] Jamet E. An eye-tracking study of cueing effects in multimedia learning.
631 *Computers in Human Behavior*. 2014;32:47–53.
- 632 [56] Hoffman G. Evaluating fluency in human–robot collaboration. *IEEE Trans Hum
633 Mach Syst*. 2019;49(3):209–218.
- 634 [57] Maurice P, Allienne L, Malaise A, et al. Ethical and social considerations for the
635 introduction of human-centered technologies at work. 2018 IEEE Workshop on
636 Advanced Robotics and its Social Impacts (ARSO) [Internet]. Genova, Italy:
637 IEEE; 2018 [cited 2023 May 3]. p. 131–138. Available from:
638 <https://ieeexplore.ieee.org/document/8625830/>.
- 639 [58] Besharati A, Daneshmandi H, Zareh K, et al. Work-related musculoskeletal
640 problems and associated factors among office workers. *International Journal of
641 Occupational Safety and Ergonomics*. 2020;26(3):632–638.
- 642 [59] Darvishi E, Maleki A, Giahi O, et al. Subjective mental workload and Its
643 correlation with musculoskeletal disorders in bank staff. *Journal of Manipulative
644 and Physiological Therapeutics*. 2016;39(6):420–426.
- 645 [60] Bauer A, Wollherr D, Buss M. Human-Robot Collaboration: a survey. *Int J
646 Human Robot*. 2008;05(01):47–66.
- 647 [61] Lemonnier S, Simonin J, Lanfranchi J-B. Robots collaboratifs dans l'industrie
648 française en 2021 : acceptation des opérateurs et points de vue d'industriels.
649 [Collaborative robots in French industry in 2021: Operator acceptance and
650 industrial viewpoints]. *IHM '23: Proceedings of the 34th Conference on
651 l'Interaction Humain-Machine* [Internet]. TROYES France: ACM; 2023 [cited
652 2023 Jun 23]. p. 1–8. Available from:
653 <https://dl.acm.org/doi/10.1145/3583961.3583979>.
- 654 [62] Grier RA. How high is high? A meta-analysis of NASA-TLX global workload
655 scores. *Proceedings of the Human Factors and Ergonomics Society Annual
656 Meeting*. 2015;59(1):1727–1731.
- 657 [63] Gagnon D, Plamondon A, Larivière C. A biomechanical comparison between
658 expert and novice manual materials handlers using a multi-joint EMG-assisted
659 optimization musculoskeletal model of the lumbar spine. *Journal of
660 Biomechanics*. 2016;49(13):2938–2945.
- 661 [64] Hoffman KA, Aitken LM, Duffield C. A comparison of novice and expert nurses'
662 cue collection during clinical decision-making: Verbal protocol analysis.
663 *International Journal of Nursing Studies*. 2009;46(10):1335–1344.
- 664 [65] Bernar A, Prevot C, Legardeur J, et al. Comment favoriser la transition vers
665 l'industrie 4.0 dans le secteur textile-habillement : étude de cas du déploiement
666 d'un cobot au sein de l'entreprise Petit Bateau. [How to foster the transition to

667 industry 4.0 in the textile clothing sector: A case study of the deployment of a
668 cobot at Petit Bateau]. 18ème Colloque national S.mart. Carry le Rouet; 2023.
669

670 Table 1. Variables measured in this study.

Type of variables	Variables measured
Performance at the collaborative task	- Number and percentage of products manufactured. - Number and percentage of steps performed.
Participant's posture	- Mean overall RULA score of a trial. - Mean RULA scores for joints during a trial. - Percentage of time spent in risk levels 2 and 3 of RULA evaluation.
Attentional demand	- Absolute error at the auditory task.
Subjective workload	- Global NASA-TLX score. - NASA-TLX score for each dimension.

671

672 Table 2. Performances at the collaborative hybrid task. Results are presented in median
 673 (IQ). ‡, § or #: for the conditions in a row, distinct symbols are indicative of significant
 674 differences between the conditions; same symbols in a row are indicative of no
 675 differences between conditions.

Variable	SLOW	MEAN	FAST
Number of products manufactured	3.0 (0.1) ‡	3.7 (0.7) §	4.0 (1.2) §
Number of steps performed	13.0 (0.1) ‡	15.7 (1.0) §	18.8 (1.8) #
Percentage of products manufactured (%)	100.0 (2.8) ‡	91.7 (16.7) §	80.0 (23.3) #
Percentage of steps performed (%)	100.0 (0.6) ‡	97.9 (6.3) §	94.2 (9.2) #

676

677 Table 3. RULA overall scores during a whole trial and during participants' Idle and
 678 Direct activity for the both sides. Results are presented in median (IQ). L and R
 679 meaning left and right sides respectively. ‡ or §: for the conditions in a row, distinct
 680 symbols are indicative of significant differences between the conditions; same symbols
 681 in a row are indicative of no differences between conditions.

Variable		SLOW	MEAN	FAST
RULA overall scores during a whole trial	L	4.48 (0.82) ‡	4.39 (0.62) ‡	4.59 (0.71) ‡
	R	4.10 (0.94) ‡	4.03 (0.98) ‡	4.29 (0.93) §
Time spent in risk level 2 of RULA evaluation (%)	L	62.9 (24.1) ‡	57.6 (25.5) §	54.0 (26.6) §
	R	71.7 (35.7) ‡	68.6 (32.1) ‡	60.2 (35.8) ‡
Time spent in risk level 3 of RULA evaluation (%)	L	29.6 (18.1) ‡	36.7 (20.2) ‡	36.9 (16.8) ‡
	R	25.4 (28.0) ‡	21.6 (24.0) ‡	32.9 (24.5) ‡

682

683 Table 4. NASA-TLX scores for each dimension. Results are presented in median (IQ).
 684 ‡, § or #: for the conditions in a row, distinct symbols are indicative of significant
 685 differences between the conditions; same symbols in a row are indicative of no
 686 differences between conditions.

Variable	SLOW	MEAN	FAST
Mental demand	10.2 (11.7) ‡	10.0 (7.6) ‡	17.2 (8.8) §
Physical demand	0.0 (3.0) ‡	0.0 (3.4) ‡	2.3 (5.1) ‡
Temporal demand	1.2 (3.7) ‡	8.7 (13.1) §	22.0 (19.0) #
Effort	3.5 (5.6) ‡	9.7 (8.0) §	11.7 (10.2) #
Performance	5.2 (3.1) ‡	5.2 (3.5) ‡	5.0 (4.7) ‡
Frustration	8.7 (14.7) ‡	7.3 (8.7) ‡	4.2 (8.7) ‡

687

688 Figure 1. A/ YuMi cobot and working plan; B/ Components to manufacture products
689 [36].

690

691 Figure 2. The central box represents the middle 50% of the data, spanning from the first
692 quartile (Q1) to the third quartile (Q3), known as the interquartile range (IQR). Inside
693 the box, a line marks the median of the data set. The whiskers extend from the edges of
694 the box to the minimum and maximum data points, excluding outliers, which are shown
695 separately. A/ Number of products manufactured in three minutes; dotted red lines
696 indicate the number of products participants had to manufacture. B/ Percentage of
697 products manufactured on total products waited. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

698

699 Figure 3. The central box represents the middle 50% of the data, spanning from the first
700 quartile (Q1) to the third quartile (Q3), known as the interquartile range (IQR). Inside
701 the box, a line marks the median of the data set. The whiskers extend from the edges of
702 the box to the minimum and maximum data points, excluding outliers, which are shown
703 separately. A/ Absolute error at the auditory task. B/ NASA-TLX scores. * $p < 0.05$. **
704 $p < 0.01$. *** $p < 0.001$.

705

706 Appendix 1: RULA scores for joints during a whole trial and during participants' Idle
707 and Direct activity for the both sides. Results are presented in median (IQ). Bold values
708 for p-value column indicate significant differences for the non-parametric Friedman's
709 repeated measures ANOVA. L and R meaning left and right sides respectively.
710 Shoulders, neck and back scores are out of 6, wrists are out of 4 and elbows are out of 3.
711 ‡, § or #: for the conditions in a row, distinct symbols are indicative of significant
712 differences between the conditions; same symbols in a row are indicative of no
713 differences between conditions.

RULA scores for joints		SLOW	MEAN	FAST	p-value
Shoulder	L	2.38 (0.15) ‡	2.50 (0.20) §	2.57 (0.19) #	p < 0.001
	R	2.32 (0.18) ‡	2.34 (0.25) ‡	2.38 (0.28) ‡	p = 0.076
Elbow	L	2.39 (0.46) ‡	2.39 (0.44) ‡	2.32 (0.47) ‡	p = 0.196
	R	1.92 (0.35) ‡	1.82 (0.39) ‡	1.81 (0.39) ‡	p = 0.076
Wrist	L	3.62 (0.25) ‡	3.55 (0.32) ‡	3.50 (0.37) ‡	p = 0.076
	R	3.60 (0.21) ‡	3.53 (0.32) ‡	3.60 (0.33) ‡	p = 0.368
Neck		2.49 (0.62) ‡	2.52 (0.89) ‡	2.50 (1.15) ‡	p = 0.854
Back		2.36 (0.74) ‡	2.57 (0.73) §	2.72 (0.66) #	p < 0.001

714