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Biomechanical effects of the addition of a precision constraint on a collective load carriage task

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14 **1 Abstract**

15 Team lifting is a complex and collective motor task that possesses both motor and cognitive
16 components. The purpose of this study was to investigate to what extent the biomechanics of a
17 collective load carriage is affected when a dyad of individuals is performing a carrying task
18 with an additional accuracy constraint. Ten dyads performed a first condition in which they
19 collectively transported a load (CC), and a second one in which they transported the same load
20 while maintaining a ball in a target position on its top (PC).

21 The recovery-rate, amplitude, and period of the center-of-mass (COM) trajectory were
22 computed for the whole system (dyad + table = PACS). We analyzed the forces and moments
23 exerted at each joint of the upper limbs of the subjects. We observed a decrease in the overall
24 performance of the dyads when the Precision task was added, i.e., i) the velocity and amplitude
25 of CoM_{PACS} decreased by 1,7% and 5,8%, respectively, ii) inter-subject variability of the
26 Moment-Cost-Function decreased by 95% and recovery rate decreased by 19,2% during PC. A
27 kinetic synergy analysis showed that the subjects reorganized their coordination in the PC.

28 Our results demonstrate that adding a precision task affects the economy of collective load
29 carriage. Notwithstanding, the joint moments at the upper-limbs are better balanced and co-
30 vary more across the paired subjects during the precision task. Our study results may find
31 applications in domains such as Ergonomics, Robotics-developments, and Rehabilitation.

32 **Keywords:** Ergonomic, Dual Task, Load Carriage, Collective Behavior, Team Lifting,
33 Precision Task.

34

35 2 Introduction

36 Individual manual materials handling is commonly performed in many human activities. Its
37 definition regroups essentially different tasks of load handling (i.e. the transport, support, lift,
38 push, pull...) and has unfavorable ergonomic conditions (Directive 90/269/CEE). Different
39 lifting techniques (Faber et al., 2007) and mechanical aids (Godwin et al., 2009) have been
40 proposed to avoid the associated leisure. However, the most common alternative used is team
41 lifting. It is, in appearance, a simple solution to carry a heavy load (i.e. too heavy to be carried
42 safely by a single individual), a bulky object without mechanical aids. This strategy is then
43 supposed to reduce the load on individuals performing the task (Sharp et al., 1997). It is also
44 used in some sports such as Crossfit discipline when lifting “worm”, a heavy, long, and soft
45 cylindrical bag (Claudino et al., 2018).

46 Furthermore, team lifting necessitates both motor and cognitive skills in order to control the
47 movement coordination. For this reason, many authors consider it as a dual-task, e.g. workdays
48 in ironwork (Faber et al., 2012). The tasks are called dual as they often undergo some
49 interference, linked to a limited ability to share attention between the two task goals. Dual-task
50 interference are commonly studied in psychology to highlight the cognitive limits of the human
51 brain (Pashler, 1994). One well-known example of these cognitive limits is based on
52 locomotion which can be used in interference paradigm (Yogev-Seligmann et al., 2008; Yogev-
53 Seligmann et al., 2010). For example, walking along an L-shaped path while performing an
54 arithmetic task deteriorates the mobility function. Any additional cognitive-task is considered
55 as a limiting factor for the motor task since it induces a modification of gait pattern e.g., reduces
56 gait speed, induces movement fluctuation and oscillation. Beach et al., (2006), showed that
57 during a repetitive lifting task adding a precision placement challenges leads to an increase of
58 lumbar spine load and an increase of the upper limb movement time.

59 Recent studies focused on lifting-Precision dual-task and showed that locomotor pattern was
60 not affected when the subjects performed a dual-task such as carrying a load (20% of mean body
61 mass) on the shoulders (Castillo et al., 2014), or carrying a load (21% and 36 % of mean body
62 mass) on the back(Ackerman and Seipel, 2014; Bastien et al., 2016). However, other studies
63 reported a walking pattern affected by the dual-task when the load is balanced on the top of the
64 head (Heglund et al., 1995) or when it is carried collectively (Fumery et al., 2018). In certain
65 jobs, a collective load transfer is simultaneously associated to a precision task (e.g. talking with
66 the patient in nurses, administrating medication in stretchers bearer, Industrial manufacturing

67 in workman). This occurs especially in paramedics or during search and rescue activities
68 (Gamble et al., 1991; Restorff, 2000; Barnekow-Bergkvist et al., 2004; Leyk et al., 2007).

69 Despite this practical relevance, only few studies deal with biomechanical aspects of collective
70 transport of a load. However, it is essential to conceive aids, exoskeletons and collaborative
71 robots dedicated to assisting humans in such a task. Fumery et al., (2018) studied the energetic
72 exchanges during a collective load carriage to investigate whether two individuals transporting
73 an object behave economically. The authors showed that the external energetic exchanges
74 occurring during this type of transport was as efficient as those occurring in single gait when
75 the load is below 10% of the total body mass of the dyad. In our study, we reproduce the
76 protocol of Fumery et al. to investigate the locomotor pattern of ten paired individuals carrying
77 a box collectively and to compare these walking patterns when this task is performed
78 simultaneously with a precision task. This precision task consists in maintaining a ball in the
79 center of a circular target drawn on the top of the box. Thanks to handle sensors and kinematic
80 data, we also record the forces and moments applied on the box then compute the constraints at
81 the arms and back joints using the inverse dynamics bottom-up procedure. The purpose of this
82 study is to investigate to what extent the performance of a collective load transport is impacted
83 when a cognitive task is performed simultaneously, and how the control of the cognitive task is
84 shared across the subjects. As it has been observed in single subjects walking and performing
85 a cognitive task, we hypothesize that gait performance of the individuals walking while
86 transporting collectively a load is disturbed when they perform a precision task requiring
87 precision. Fumery et al. (2018) demonstrating that the pattern of a dyad carrying a light load
88 was not affected by the collective task, our hypothesis is that, using the same load ratio, the
89 precision task is the single factor affecting the walking-carrying pattern of the paired subjects.

90 **3 Materials and Methods**

91 **3.1 Population**

92 Ten pairs of healthy male individuals (mean±s.d.: volunteer 1 - at the left side of the load: height
93 = 1.77±0.07 m, mass = 74.78±9.00 kg; volunteer 2 - at the right side of the load: height =
94 1.77±0.05 m, mass = 74.54±12.38 kg) participated in the experiments. The individuals had no
95 orthopedic disabilities, no dysfunctions of the locomotor system, no neurological or vestibular
96 diseases, no visual deficits and no proprioceptive disorders or dementia.

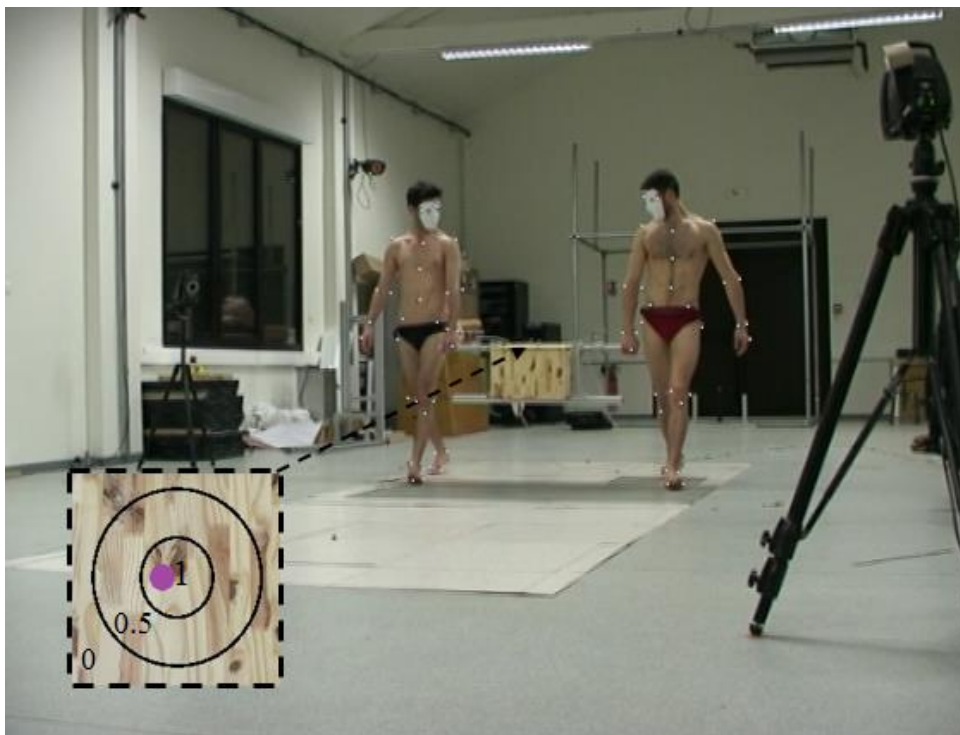
97 This study was carried out in accordance with the requirement of a non-interventional study
98 given by the CNRS bioethical office. The study was approved by the Research Ethics

99 Committee of the University of Toulouse, France (number IRB00011835-2019-11-26-172,
100 Université Fédérale de Toulouse IRB #1). All subjects gave verbal and written informed
101 consent in accordance with the Declaration of Helsinki.

102 3.2 Experimental Protocol

103 Two conditions were performed by the subjects. In the first condition (Control Condition: CC)
104 they walked side by side at spontaneous speed while carrying a box (mass = 13.41 kg, size:
105 0.40x0.40x0.28 m) equipped with two lateral handle sensors (Sensix, France). The mass of the
106 box plus the sensors was 14.250 kg thus almost 10% of the body-mass of the two volunteers.
107 In order to get accustomed to the task the subjects performed three successive trials. Only the
108 last and third trial was retained for the analysis.

109 In the second condition (Precision Condition: PC), the individuals were instructed to transport
110 the box, while performing an accuracy task consisting in keeping a ball (diameter: 19mm, mass:
111 2g) in the center of a circular target drawn on the top of the box (Fig 1). Subjects were not
112 allowed to orally communicate during the experiments.



113

114 **Figure 1. Experimental setup: Collective load carriage performed with a precision task (PC).**

115 The dyad carried a box (mass = 13.41 kg, size: 0.40x 0.40 x 0.28) while maintaining a ball
116 (diameter=19mm, mass=2g) in the center of a targeted position (diameter of the small and large circle:
117 120 mm and 240 mm respectively) on its top. If the ball was maintained in the small circle, the dyad

118 obtained a 1-point Scorep. If it was maintained between the small and large circle, then they obtained
119 0,5-point Scorep. Else, they obtained 0-point Scorep.

120 **3.3 Kinematic and Kinetic Data Acquisition**

121 Motion capture data were collected using thirteen infrareds (11 MX3 and 2 TS40) transmitter-
122 receiver video cameras (Vicon[®], Oxford metric's, Oxford, United Kingdom) sampled at 200
123 Hz. Forty-two retro-reflective markers were placed on bony landmarks and on the navel of each
124 subject (according to Wu et al., 2002, 2005) and fourteen on the box. The ball used during the
125 PC tests was reflective as well and was tracked by the Vicon[®] system.

126 In order to record the gait pattern at constant speed (i.e. to exclude the acceleration and
127 deceleration phases at the beginning and end of each trial) the volume calibrated by the Vicon[®]
128 system (30 m³) was located in the middle of the 20m-long walkway crossed by the subjects.
129 The reflective marks were tracked to define the kinematics of the Poly-Articulated Collective
130 System (PACS) formed by the two individuals and the load they carry (Zatsiorsky, 1983;
131 Moretto et al., 2016). The data were recorded on one gait cycle defined by the first heel strike
132 of the first subject and the third heel strike of the second subject of the PACS to ensure a cycle
133 of each subject. The 3D reconstruction was performed using Vicon Nexus 1.8.5[®] software.

134 The two lateral handles used to transport the box were equipped with Sensix[®] force sensors
135 sampled at 2000 Hz. A 4th order Butterworth filter and a 5 Hz and 10 Hz cut frequency have
136 been applied to analyze the positions of the markers and the forces exerted on the box handles,
137 respectively.

138 **3.4 Computed parameters**

139 **3.4.1 Trajectory of the CoM_{PACS}**

140 The De Leva Anthropometric tables (de Leva, 1996) was used to estimate the mass m_i and the
141 CoM of each segment i (CoM _{i}) of the PACS and to compute its global CoM (CoM_{PACS}) as
142 follow:

$$143 \quad \mathbf{G}_{PACS} = \frac{1}{m_{PACS}} \sum_{i=1}^{n=33} m_i \mathbf{G}_i \quad (1)$$

144 with \mathbf{G}_{PACS} the 3D position of the CoM_{PACS} in the frame R (the global coordinate system),
145 m_{PACS} the mass of the PACS, n the number of PACS segments (i.e. 16 segments per volunteer
146 plus one segment for the box) and \mathbf{G}_i the 3D position of the CoM _{i} in the frame R. The CoM of

147 the box was determined at the intersection point of the vertical lines obtained by hanging it with
148 a thread fixed at different positions. The material used for the box construction, i.e. wood and
149 aluminium, was considered as not deformable.

150 According to Holt et al., (2003), the amplitude ($A = Z_{\max} - Z_{\min}$, with Z the height of the
151 CoM_{PACS}, in meters,) and the period (peak to peak, in percent of the gait cycle) of the CoM_{PACS}
152 were also assessed.

153 The forward kinetic (W_{kf}), as well as the vertical (W_v) and external work (W_{ext}) of the CoM_{PACS}
154 were computed according to the method of Bastien et al. (2016). Then based on the external
155 work, the percentage of energy recovered of the CoM_{PACS} in the sagittal plane was computed
156 (called recovery rate RR in Fumery et al., 2018a, 2018b). This parameter assess the amount of
157 energy transferred between the potential and the kinetic energy (Eqn 2).

$$158 \quad RR = 100 \frac{W_{kf} + W_v - W_{ext}}{W_{kf} + W_v} \quad (2)$$

159 The closer the value of RR to 100%, the more consistent the locomotor pattern is with the
160 inverted pendulum system (IPS) model of locomotion (Cavagna et al., 1963; Willems et al.,
161 1995; Gomeñuka et al., 2014; Bastien et al., 2016). In this study, the trajectory of CoM_{PACS} and
162 CoM of an inverted pendulum have been investigated.

163 **3.4.2 Forces and moments at the joints of the upper limbs**

164 Sensix force sensors recorded the forces and moments applied by each individual on the two
165 box handles. Before the computation, the data of the sensors located by specific markers were
166 transfer to the Galilean frame of the laboratory using rotation matrix. A cross correlation
167 method has been applied in order to analyze the coordination between the forces produced by
168 both subjects. To investigate whether the movement of the box results from an action-reaction
169 strategy, we computed the time lag required for the position of the left side and right side of the
170 box to be the same on the medio-lateral, antero-posterior and vertical axis in CC and PC. The
171 coordination was assessed through the forces exerted on three directions (medio-lateral, antero-
172 posterior and vertical axis). This results will reflect the level of coordination of two subjects
173 during a collective transport

174 In order to quantify muscular constraints produced at the upper limb, the Inverse Dynamic
175 Method was used to estimate forces and moments at each joint of the upper limb. The Moment
176 Cost Function was then computed ($\text{kg.m}^2.\text{s}^{-2}$, Costes et al., 2018) as follow :

$$\begin{aligned} 177 \quad MCF &= \sqrt{M_{L_wt}^2} + \sqrt{M_{R_wt}^2} + \sqrt{M_{L_el}^2} + \sqrt{M_{R_el}^2} + \sqrt{M_{L_sh}^2} + \sqrt{M_{R_sh}^2} + \sqrt{M_{back}^2} + \\ 178 \quad &\quad \sqrt{M_{neck}^2} \quad (3) \end{aligned}$$

179 Where M_{L_wt} , M_{R_wt} , M_{L_el} , M_{R_el} , M_{L_sh} , M_{R_sh} , M_{back} and M_{neck} are the mean values over a
180 PACS gait cycle of the three-dimensional left and right wrist, left and right elbow, left and right
181 shoulder, top of the back and neck moments, respectively. $\sqrt{M^2}$ represents the Euclidian norm
182 of M (i.e. $\sqrt{M^2} = \sqrt{\sum_{i=1}^3 (M_i)^2}$, with M_i the i^{th} component of the vector M).

183 Then, the MCF values of each individual was summed to obtain the total moment cost function
184 (Total MCF). This Total MCF allows to quantify the global effort produced at the upper-limbs
185 of the PACS during one gait cycle. Finally, the MCF difference (ΔMCF) was computed as the
186 difference between the two individuals to investigate whether the subjects produced the same
187 effort in the upper limbs during the load transport.

188 3.4.3 Kinetic synergy analysis

189 We extracted the synergies by using a principal component analysis (PCA) applied to the wrist,
190 elbow, shoulder, back, and neck joint moment on the right and left sides of the body. The PCA
191 was used to reduce data dimensionality. It consisted in the eigen-decomposition of the co-
192 variance matrix of the joint moment data (Matlab *eig* function). The joint moments data from
193 one trial per condition were arranged in time \times joint moment matrices. In this analysis we only
194 used the y-component which is very close to the norm of the 3D joint moments, except that the
195 y-component (medio-lateral) could be positive and negative. The joint moments were
196 normalized by their amplitude and centered (mean removed) before application of the PCA. We
197 called the eigenvectors extracted from the PCA, dynamic synergy vectors. We computed the
198 VAF (Variance Accounted For) which corresponded to the cumulative sum of the eigenvalues,
199 ordered from the greatest to the lowest value, normalized by the total variance computed as the
200 sum of all eigenvalues. The synergy vectors retained were then rotated using a Varimax rotation
201 method to improve interpretability.

202 We first extracted the synergy vectors for each experimental condition and each participant
203 separately. In this analysis the initial data matrices were constituted of all available time frames
204 in line, concatenated from one trial per condition, and of eight columns corresponding to each
205 joint moment, namely the right wrist, left wrist, right elbow, left elbow, right shoulder, left

206 shoulder, back, and neck. Based on a previous study we extracted 3 synergies in this analysis.
207 We then performed a second analysis to identify possible co-variations between the joint
208 moments of the two participants in each pair. The columns of the initial matrices were thus
209 constituted of the joint moments of the two loaded arms, i.e., the right wrist, elbow, and shoulder
210 joint moments of participant #1, plus the left wrist, elbow and shoulder joint moments of
211 participant #2. Based on a previous study we extracted 2 synergies in this analysis. We used
212 Pearson's r to order the different synergies similarly between the different subjects and
213 conditions.

214 **3.4.4 Accuracy score**

215 A performance score ($score_p$) was assigned to each image of the videos captured by the Vicon[®]
216 system (200 images/s). The score depended on the location of the ball in the target: 1 when the
217 ball was inside the small circle, 0.5 when it was in-between the small and large circle and 0
218 when it was outside the large circle. The accuracy over the whole gait cycle was measured by
219 an overall score ($Score_{accuracy}$), expressed in percentage, and calculated as follows:

$$220 \quad \text{Score}_{accuracy} = \frac{\sum \text{Score}_p \times 100}{t_{\text{gait cycle}}} \quad (4)$$

221 where $t_{\text{gait cycle}}$ represents the number of Vicon[®] images recorded along one gait cycle.

222 **3.4.5 Orientation of the upper part of the body**

223 The head, shoulders and pelvis rotation angles were computed around the vertical axis of each
224 individual in the two conditions. The angle was positive when the subjects turned towards the
225 box they carried, otherwise it was negative. The distance between the forehead and the sternum
226 (distance FOR-STE) was also computed in order to investigate the flexion of the cervical spine.

227 **3.5 Data analysis**

228 The data were analyzed with Matlab R2016b[®] and StatView 5.0[®] software. A paired t-test was
229 used to compare the RRs, the amplitudes, the periods, the velocities of the vertical displacement
230 of the CoMPACS, the head, shoulders and pelvis rotation angle and the length FOR-STE
231 between the CC and PC condition. The significance threshold was set to 0.05. We computed
232 with a cross-correlation method the time lag required for the position of the left side and right
233 side of the box to be the same on the medio-lateral, antero-posterior and vertical axis in CC and
234 PC.

235 We used the average subspace angles to compare the subspaces spanned by the synergy vectors
236 (Knyazev and Argentati, 2002). In order to decide whether the subspaces were more similar
237 than expected by chance, the confidence interval (CI) of random comparisons was computed.
238 For this analysis, we generated pairs of random subspaces constituted each of either 3 unit
239 vectors of dimension 8 (individual PCA analysis) or 2 unit vectors of dimension 6 (conjoint
240 PCA analysis) and computed the mean subspace angle between them. The unit vectors were
241 built using normally distributed pseudo-random numbers (Matlab randn function). We
242 performed 10000 simulations in order to determine the 95%-CI of the mean subspace angle
243 between the pairs of random subspaces. The confidence interval was 39.5° – 70.0° ($55.0 \pm 7.6^{\circ}$)
244 for the individual PCA analysis and 36.3° – 79.1° ($57.7 \pm 10.7^{\circ}$) for the conjoint analysis.

245 We used Student tests for single mean to compare the subspaces angles to the lower bound CI
246 with the assumption that similarity was higher than expected by chance when the angles were
247 lower than the lower bound CI.

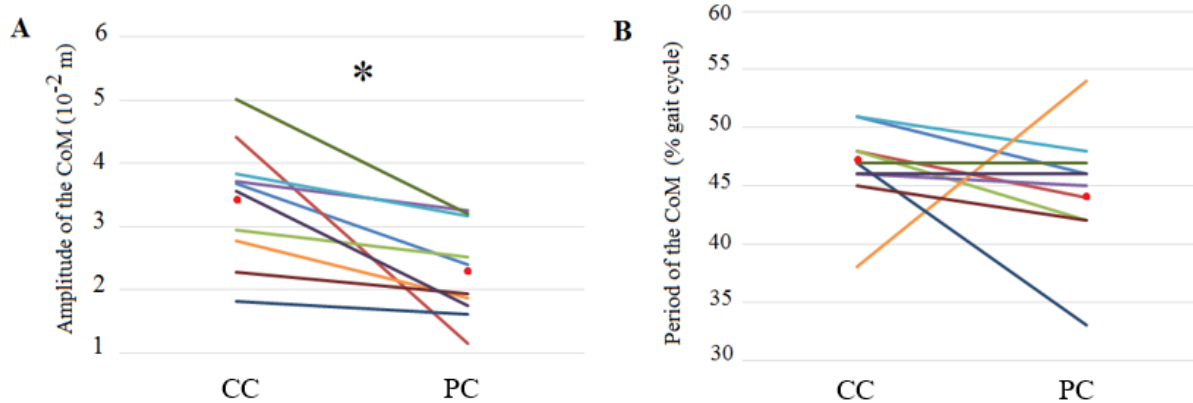
248 VAFs were compared with an ANOVA with one repeated measure (control vs. precision
249 conditions) and one factor (participant #1 vs. participant #2) when synergies were extracted
250 separately for each subject. For the conjoint analysis, a paired Student t-test was used. Subspace
251 angles were compared with t-tests for dependent samples (paired t-test) when comparing the
252 control and precision conditions and t-test for independent samples when comparing the two
253 participants. Adjustments for multiple comparisons were performed by Bonferroni's method.
254 Initial level of significance was set to $p < 0.05$.

255 **4 Results**

256 **4.1 Dynamics analysis of the dual-task**

257 **4.1.1 CoM trajectory**

258 The CoM_{PACS} velocity significantly decreased from $1.40 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$ in CC to $1.23 \pm 0.17 \text{ m}\cdot\text{s}^{-1}$
259 in PC ($t = 3.385$, $p = 0.008$). The CoM_{PACS} amplitude (Fig. 2A, $t = 3.704$, $p = 0.005$), significantly
260 decreased from $2.87 \pm 0.742 \text{ cm}$ in CC to $2.29 \pm 0.739 \text{ cm}$ in PC (Table S3). However, the
261 period of the CoM_{PACS} oscillation was not significantly affected by the precision task (Fig. 2B,
262 $t = 0.842$, $p = 0.422$).

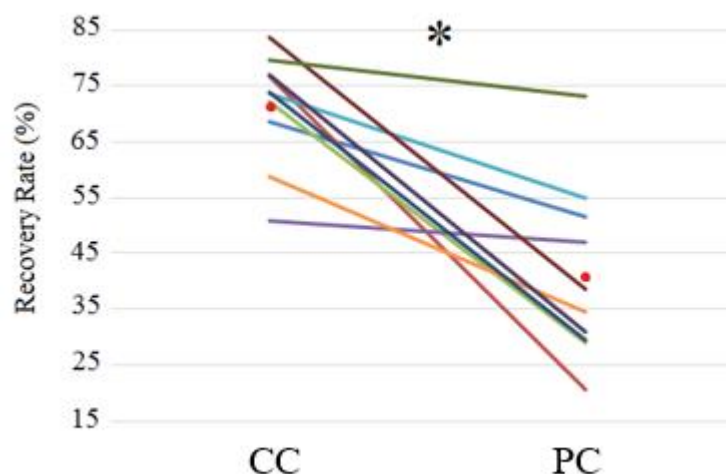


263

264 **Figure 2. Amplitude (A) and period (B) of the vertical displacement of the CoMPACS in the**
265 **Control Condition (CC) and the Precision Condition (PC).** The mean value of each dyad (N=10)
266 was computed for the CC and PC and linked. The red points represent the mean for each condition.
267 The same color is assigned to each dyad in all figures. * = significant difference (p<0.05 paired t-test).

268

269 The percentage of energy recovered at the CoM_{PACS} significantly decreased between CC and
270 PC (t=5.18, p<0.001) (Fig 3). This showed an alteration of the efficiency of the locomotor
271 pattern of the dyad when the energy transfer between the potential and the kinetic energy was
272 by 19,2% lower in PC compared to CC.



273

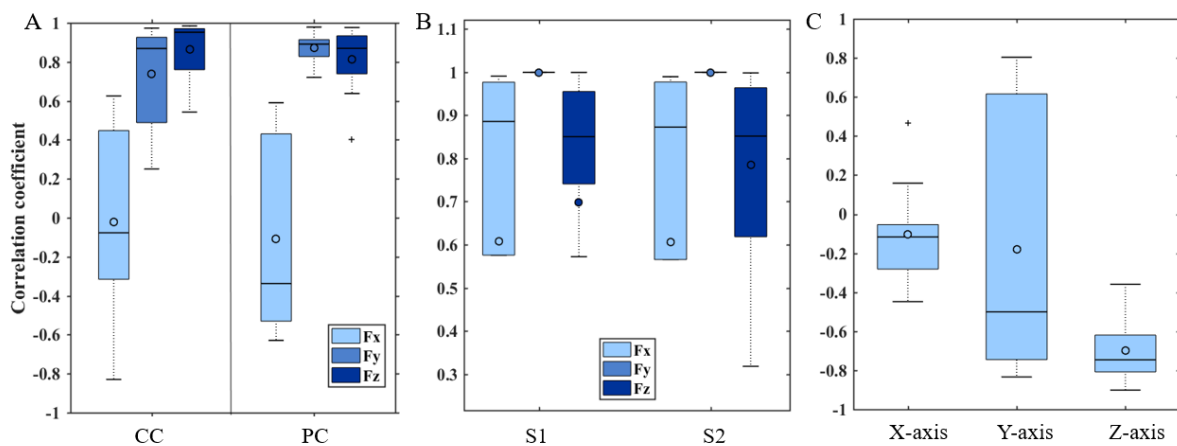
274 **Figure 3. Recovery Rate (%) of each dyad (N=10) during Control Condition (CC) and Precision**
275 **Condition (PC).** The red points represent the mean for each condition. The same color is assigned to
276 each dyad in all figures. * = significant difference (p<0.05 paired t-test).

277

278 4.1.2 Forces applied to the handles

279 Significant differences were found between the correlation coefficients of the three components
280 (x, y, z) of the forces applied to the handles by the subjects of the dyad for each condition. In
281 the CC condition, R_{F_x} was lower than R_{F_y} ($t = -3.45$, $p < 0,001$) and R_{F_z} ($t = -4.53$, $p < 0,01$) and
282 R_{F_y} was lower than R_{F_z} ($t = -2.48$, $p = 0,04$). In the PC condition, R_{F_x} was lower than R_{F_y} ($t = -$
283 6.06 , $p < 0,01$) and R_{F_z} ($t = -4.50$, $p < 0,01$). However, no significant differences (Fig. 4A) were
284 found between the CC and the PC conditions ($t = -0.43$, $p = 0.675$; $t = -1.43$, $p = 0.188$; $t = -$
285 1.02 , $p = 0.335$ for the medio-lateral, antero-posterior and vertical axis, respectively) (Table
286 S8).

287 In the CC, the time lags were lower than 150 ms in the medio-lateral and antero-posterior axis
288 and only one lag was higher than 150 ms for one dyad for the vertical axis (Table 1, lagZ $20 \pm$
289 50 ms). Concerning the PC, the time lags were also lower than 150 ms in the medio-lateral and
290 antero-posterior axis and five dyads had a time lag higher than 150 ms for the vertical axis
291 (Table 1, lagZ 180 ± 230 ms) (Table S7).



292
293 **Figure 4. Boxes plot showing the distribution of the correlation coefficient (Coef).** A : Coef of the
294 forces produced by the individuals in each dyad on the box handles, on the medio-lateral (Fx), antero-
295 posterior (Fy) and vertical axis (Fz) in the CC and PC conditions. B : Coef of the ball displacement
296 and the handles displacement, on Fx, Fy, and Fz, in the CC and PC conditions. C : Coef of the ball
297 trajectory and the sum of forces exerted by the subjects on the handles, on Fx, Fy, and Fz, in PC. N =
298 10 for each condition. * $0.05 > p > 0.01$; ** $p < 0.01$ (paired Student t test). The upper horizontal line of
299 the box represents the third quartile (75th percentile), the lower line of the box represent the first
300 quartile (25th percentile), the middle value of the dataset is the median value (50th percentile) and the
301 upper and lower horizontal lines outside the box represent respectively 90th percentile and 10th
302 percentile. Cross-and circle represent respectively outlier and mean.

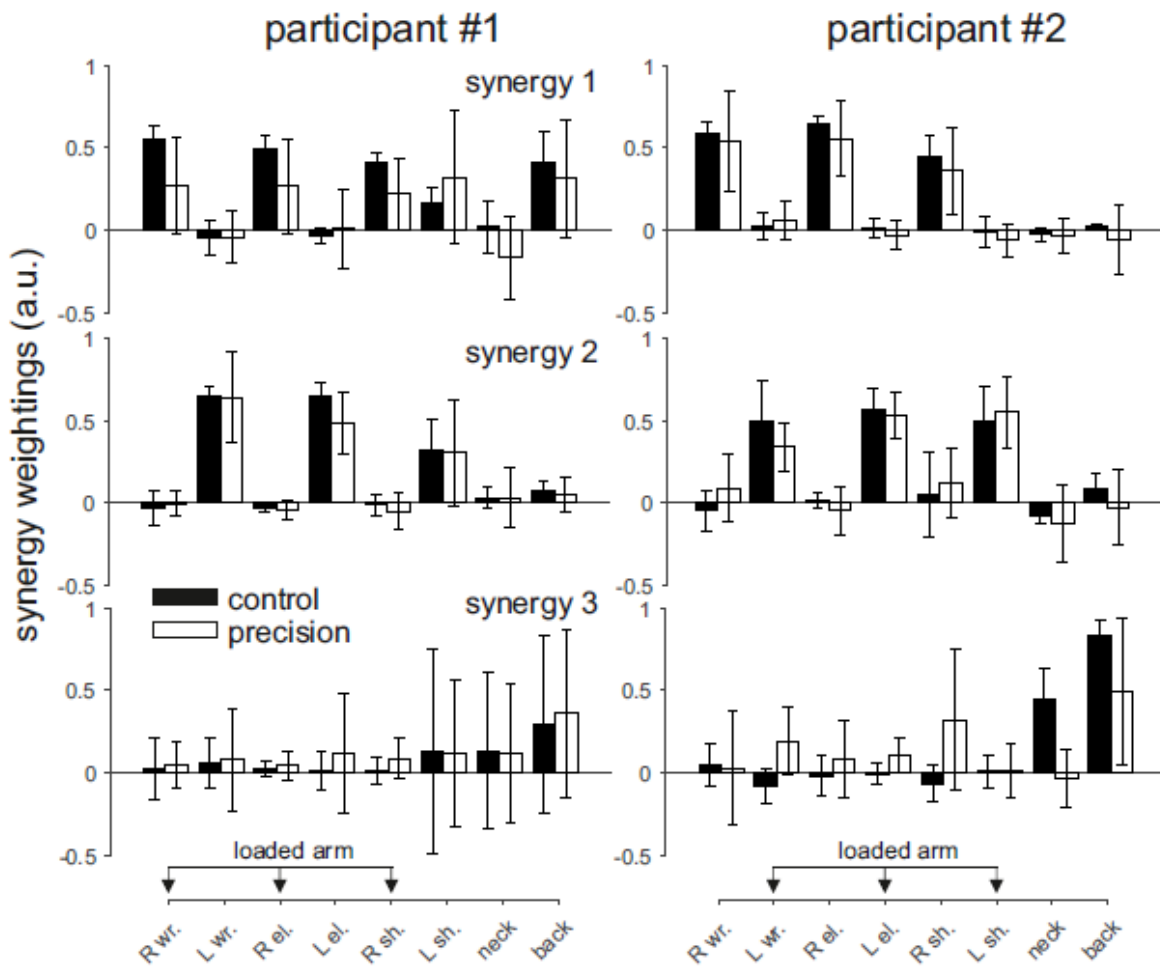
303 **4.1.3 Kinetic synergy analysis**

304 Consistent with a previous study we extracted 3 dynamic synergies for all subjects, which
305 accounted for 96.3 ± 2.0 % of total variance on average (range [90.0–99.0]%). We found no
306 effect of the side (being on the left or right side of the load) nor of the precision constraint on
307 the VAF values (i.e., $|\Delta\text{VAF}|=1.9\pm 0.4\%$, p -value = 0.24, $\eta^2=0.08$ and $|\Delta\text{VAF}|=0.9\pm 0.5\%$, p -
308 value = 0.62, $\eta^2=0.01$, respectively).

309 The dynamic synergies for each participant are depicted in Fig 5. The comparisons between
310 participant #1 and participant #2 gave subspaces angles not different than expected by chance
311 in the precision condition (i.e., $45.0\pm 10.0^\circ$ compared to 39.5° , Student $t_9=-1.34$; p -value=0.21;
312 Fig. 6A). For the other comparisons in Fig 6, subspace angles were lower than expected by
313 chance (Fig 6, $|\text{Student } t_9|\geq 7.6$; p -value<0.001). The subspace angles were lower in the control
314 condition than in the precision condition when comparing participant #1 and participant #2 (Fig.
315 6A, Cohen's $d= 1.9$; Student $t_9=-4.95$; p -value<0.001); showing an effect of the conditions on
316 inter-subject similarities. The comparison between the control and precision conditions gave
317 subspace angles of $27.2\pm 5.7^\circ$ on average with no differences between subjects (Fig. 6B,
318 Cohen's $d= 0.61$; Student $t_9=-1.93$; p -value=0.09). The inter-condition subspace angles were
319 lower than inter-subject subspace angles (i.e., $27.2\pm 5.7^\circ$ vs. $37.1\pm 7.7^\circ$, Cohen's $d= 1.5$; Student
320 $t_{18}=3.30$; p -value=0.004).

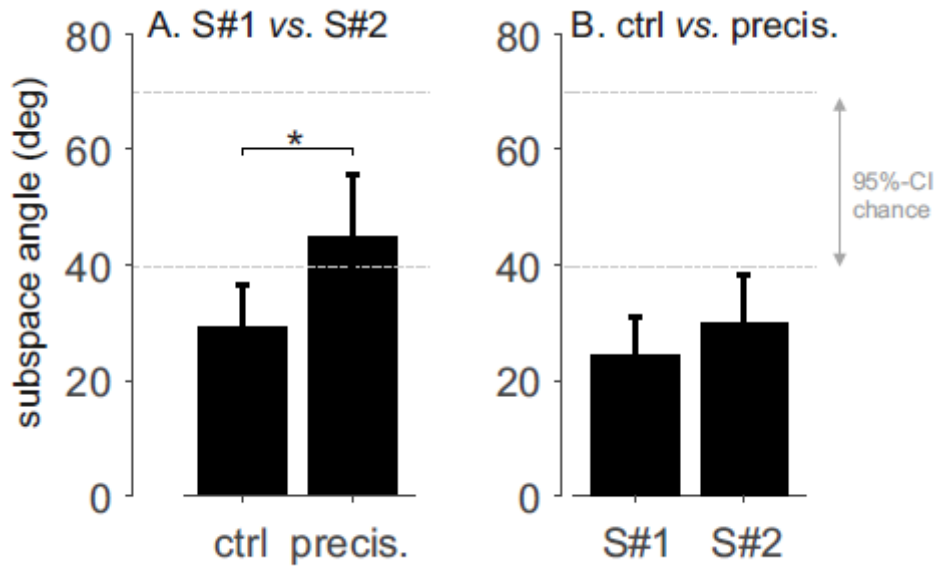
321 For the conjoint PCA analysis, two dynamic synergies were extracted for all pairs of subjects,
322 which accounted for $95.1\pm 3.5\%$ of total variance on average (range [84.4–98.8]%). The
323 dynamic synergies for the conjoint analysis are depicted in Fig 7. VAFs were similar in the
324 control and precision conditions ($96.6\pm 2.5\%$ vs. $93.5\pm 3.8\%$, respectively, Cohen's $d=0.7$;
325 Student $t_9=2.18$; p -value=0.06). The subspace angles were not different than expected by
326 chance (i.e., $46.4\pm 21.3^\circ$ compared to 36.3° , Student $t_9=1.50$; p -value=0.17) when comparing the
327 control and precision conditions (Fig. 7B).

328



329

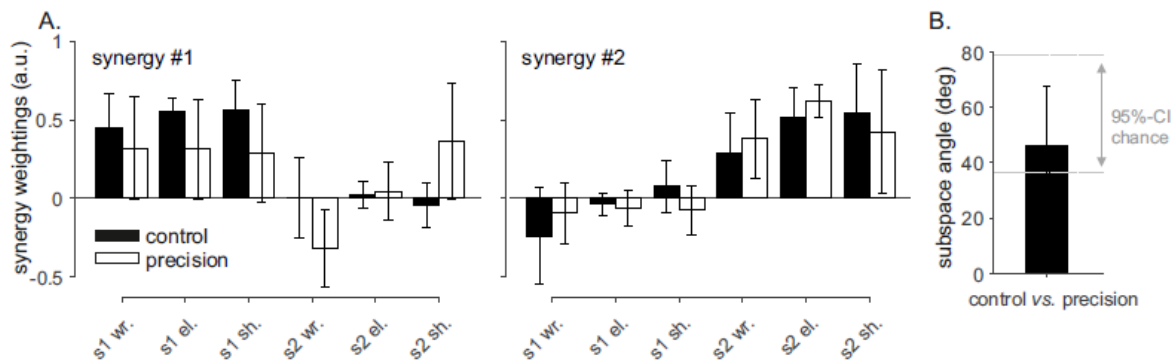
330 **Figure 5. Dynamic synergy vectors.** Three synergies accounted for more than 90.0% of total variance
331 in all subjects and conditions. Participants labeled #1 were on the right side of the load and
332 participants #2 on the left side. Wrist, elbow and shoulder were abbreviated to wr. el. and sh.
333 respectively. R and L refer to right and left side, respectively.



334

335 **Figure 6. Subspaces comparison.** The subspace angle measures the similarity between the subspaces
336 spanned by the dynamic synergies. The 95%-confidence interval of angles obtained with random
337 synergies (95%-CI chance) is indicated, i.e., CI=[49.5°,70.0°]. the star (*) indicates a significant
338 difference (i.e., $p < 0.001$).

339



340

341 **Figure 7. Conjoint synergies.** S1 and S2 refer to participants #1 (right side) and participant #2 (left
342 side), respectively. The 95%-confidence interval of angles obtained with random synergies (95%-CI
343 chance) is indicated in panel B, i.e., CI=[36.3°,79.1°].

344

345 **4.1.4 Moment Cost Function (MCF)**

346 In the CC the results obtained were divided into two different groups of dyads. Five dyads
347 showed higher values of both Total *MCF* (Fig. 8A), ($339,35 \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-2} \pm 20,44$) and ΔMCF (Fig.
348 8B) while five other dyads showed lower values, ($169,17 \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-2} \pm 17,06$).

349 Regarding the PC, the results of Total and ΔMCF (respectively $172,66 \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-2} \pm 19,16$; $5,78$
350 $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2} \pm 12,85$) were less variable than in the CC.

351 **4.2 Added task**

352 **4.2.1 Accuracy score based on the ball trajectory**

353 Regarding the ball trajectory, we found a correlation between the displacement of the handle
354 and the ball on X-axis (Medio-lateral axis). The same goes for the displacement on the y-axis
355 which represent the Postero-anterior axis (Fig. 4B). On the vertical Z-axis, the ball displacement
356 and the handle are positively correlated.

357 Correlations were also computed in order to study the relationship between the ball trajectory
358 and the sum of forces exerted by the subjects on the handles (Fig. 4C). Only two of ten dyads
359 had a correlation on the X-axis; a positive correlation for the dyad 1 and a negative correlation
360 for the dyad 10. On the Y-axis five of ten dyads had a significant negative correlation compared
361 to the other three dyads who had a significant positive correlation. For the vertical Z-axis, nine
362 of ten dyads had a positive significant correlation.

363 **4.2.2 Accuracy score**

364 The mean $\text{Score}_{\text{accuracy}}$ was 80.45 ± 23.66 % during one gait cycle of the PACS in the PC
365 condition.

366 **4.3 Head and Trunk**

367 Table 2 shows that when individuals had to keep the ball in the center of the target they turned
368 the upper part of their body towards the box. Indeed, across the CC and the PC condition the
369 orientation towards the box increased by 57.42, 9.22 and 3.29 degrees for the head, shoulders
370 and pelvis, respectively. Also, the distance FOR-STE decreased by 7.69 cm between the CC
371 and PC conditions, showing that the subjects were gazing at the box (Table S5).

372 5 Discussion

373 In this experiment, 10 dyads transported a load in two different conditions: a Control Condition
374 (CC), in which they walked together while transporting a load, and a Precision Condition (PC),
375 in which they walked together while transporting a load and maintaining at the same time a ball
376 on its top. The first objective of our study was to test the hypothesis that the gait performance
377 of two individuals walking together while transporting a load (CC) is disturbed when a precision
378 task is added (PC).

379 We studied the center of mass of the system formed by the paired subjects and the box they
380 carried. The result showed that the CoM_{PACS} speed decreased when the precision constraint was
381 added. Besides, the second task induced a decrease in the pendular behavior and amplitude of
382 the system. However, the period of the CoM_{PACS} displacement was not affected in PC. These
383 results could be expected as the added task can be considered as a fine motor skill (Exner,
384 2001). Indeed, and as observed for the gait of an adult performing a dual-task (Yogev-
385 Seligmann et al., 2010), the individuals needed to reduce their speed to perform both tasks.
386 Similar to the findings of Holt et al., (2003) in a single carrier, the decrease in speed was
387 accompanied by a decrease in the CoM_{PACS} vertical amplitude. These adaptations are
388 reminiscent of the classic speed-accuracy tradeoff and the reduction in speed is very likely a
389 strategy to reduce motor noise and improve controllability.

390 To explore the task further, we also studied each subject as a distinct entity. The comparison of
391 the individual CoM trajectory of both subjects for CC and PC did not show any significant
392 difference. Indeed, when walking side-by-side with a sensory interaction subject tend to
393 synchronize their walking pace and kinematics (Schmidt and Turvey, 1995; Zivotofsky et al.,
394 2012). The same goes for the CoM parameters (velocity, and CoM amplitude), i.e., no
395 significant differences were found between the subjects at the left and the one at the right. The
396 comparison of joint angles showed only a significant difference in hip angles between subjects.

397 No matter the condition they performed, the subjects tend to synchronize their speed and gesture
398 frequency. However, the precision task altered the CoM_{PACS} kinematics leading to a less
399 efficient energy transfer. In fact, this spatio-temporal strategy induced a decrease of the
400 pendulum-like behavior at the CoM_{PACS} .

401 Here, the energy recovered (RR) values obtained for the PACS in the CC (mean $\pm CI_{0.95}$ = 60.25
402 ± 8.57 %) were similar to those obtained in single carriers alone, as measured by Bastien et al.

403 (2016) in Nepalese porters and in untrained individuals ($RR = 61\%$), or by Tesio et al., (1998)
404 in healthy individuals ($RR = 60\%$). Our results showed a significant RR decrease in PC. This
405 confirms the CoM_{PACS} pendulum-like behavior alteration. The potential and kinetic energy
406 being out of phase, RR decrease leads to a higher mechanical cost of the whole system due to
407 the precision task. On the other hand, the global muscular efforts estimated thanks to the
408 moment cost function (MCF) of the upper-limbs were much more balanced between the
409 individuals of each dyad when they performed the dual-task than in the lifting condition (Fig
410 8).

411 Doi et al., (2011) demonstrated that increasing the difficulty of a task (e.g., dual-task) affects
412 the cost of the movement in elderly adults. Similarly, we found a modification in the trunk
413 posture in PC that might have resulted in a finer control of the task. During PC, subjects
414 spontaneously oriented their head, shoulders, and pelvis towards the box, probably to gather
415 more visual information. Modification on the orientation of the upper part of the body seems to
416 allow the subjects to look at the ball on the top of the load but, at the same time, these body
417 segments were locked in a position that likely disturbed the kinematic of the PACS and his
418 ability to behave as a pendulum. This interpretation is in accordance with the findings of Winter
419 (1995), who suggested that during a bipedal walking, the control of the trunk restrains vision
420 and head control. Here, the swings and rotations of these segments (head, shoulders, and pelvis),
421 while locked during a gait cycle, do not contribute to the CoM_{pacs}-evolution to time but may
422 explain the lower-pendulum-like behavior in the PC. The decrease of the vertical amplitude of
423 the CoM_{PACS} with both trunk and head fixed to look at the ball reveals a lower limbs pattern
424 altered in PC. Numerous research studied the impact of the trunk posture on gait pattern,
425 whether for medical purposes (Moraud et al., 2018) or sport performance purposes (Teng and
426 Powers, 2014; Huang et al., 2019). These studies showed that a modification of trunk posture
427 on the frontal and sagittal plane influences the bilateral lower limb kinematics and muscle
428 activity. Here, the control of the walking speed and of the ball may have been supported by the
429 lower legs and induced the dissipation of the mechanical energy thanks to eccentric work of the
430 muscles.

431 The impact of the added task on the physical action of the subjects during the load transport
432 was investigated. We recorded the forces applied by the subjects on the two box handles (Fig
433 4) during CC and PC. The subjects' coordination was investigated through the correlation
434 coefficient of applied forces. The results showed, in both conditions, a positive correlation for
435 the forces on the antero-posterior and vertical axis. However, the correlation on the medio-

436 lateral axis was weaker, with a large variability between the dyads of individuals. Thus, it
437 seemed that the individuals coordinated their forces to move the load in the up-down and
438 forward directions, without adopting a common strategy for the left-right direction. The results
439 were similar between the two conditions, showing that the second task did not affect the
440 collective strategies used during a simple load carriage task.

441 We considered that an action-reaction strategy was involved when the lag was higher than 150
442 ms, which corresponds to the minimum latency observed to take a decision after the perception
443 of a stimulus (VanRullen and Thorpe, 2001). All lags were lower than 150 ms in the medio-
444 lateral and antero-posterior axis. On the vertical axis however, lags higher than 150 ms were
445 found in one dyad in the CC and in five dyads in the PC. Therefore, a modification of the
446 behavior for half of the dyads was observed when the second task, requiring accuracy and
447 precision, was added. These results might suggest a more conscious control of the box. It seems
448 that the individuals moved the ball essentially by applying forces on the vertical axis at the
449 handle inducing the rotation of the box around its anteroposterior axis and the displacement of
450 the ball along the declination. When the box was thus moved by one individual, the second
451 individual reacted (with a reaction time >150 ms) by moving it in the same direction in order
452 to keep the ball in the center of the target.

453 Then, we used the moments applied on the box's handles to compute through an inverse
454 dynamic method the constraints at the joints of both upper-limbs of each subject. We observed
455 a large variability of the joint moments among dyads in the CC. Half of the dyads produced
456 much greater efforts than the other half and within this half, the joint moments produced by
457 each individual were very unbalanced. In the precision condition, each individual within these
458 five dyads produced similar efforts to keep the ball inside the circular target and to displace the
459 load during a whole gait cycle. In both conditions, the participants were not allowed to
460 communicate. However, in order to maintain the ball inside the target in the PC the dyad had
461 to gaze at the box. Research on collective tasks showed that when sharing visual information's
462 of their performance, group members tend to coordinate their forces and movements (Bosga
463 and Meulenbroek, 2007; Schmidt et al., 1998; Schmidt and Turvey, 1995). Hence, the visual
464 feedback could have an impact on the muscular effort variability between dyads, as well as
465 between individuals within each dyad.

466 These results suggest that the load carriage was affected by the second task, independently of
467 the individuals' performances in this task. Indeed, the accuracy score was not correlated

468 (r=0.31, p=0.386) to the *RR*. The accuracy score was high, suggesting a good investment of the
469 participants in the second task. According to Yogev-Seligmann et al., (2008) walking is a
470 complex motor activity, which requires both the mobilization of executive functions, i.e. the
471 cognitive capacities that allow an immediate adaptation of the motor behavior, and precision.
472 On one hand, the decrease in locomotor performance in the precision condition could be
473 explained by an increase in precision and a decrease in the mobilization of the executive
474 functions used in locomotion. In the other hand, it also could be explained by a strategy of
475 prioritization due to a structural interference between the precision needed to realize the first
476 and the second task. Ebersbach et al., (1995), concluded that even when a task is highly
477 practiced (e.g walking), adding concurrent tasks would lead to strategy changes depending on
478 the attentional demand. Indeed, these control strategies are commonly used for humanoid robot
479 when generating a movement prioritization. Sentis and Khatib, (2005), proposed a multi-level
480 control hierarchy where the global task is decomposed into several subtasks. The hierarchy used
481 ensured that constraints and critical task were accomplished first, while optimizing the
482 execution of the global task. However, the absence of correlation between the accuracy score
483 and the *RR* value reveals that the precision task may be too easy and may not discriminate
484 different levels of precision.

485 Concerning the kinetic synergy analysis, a first observation is the non symmetry in terms of
486 vector weightings for the loaded and unloaded arms i.e., the wrist, elbow and shoulder joint
487 moments co-vary more with the neck and back joint moments for the loaded arm than for the
488 unloaded arm, as demonstrated by high weightings coefficients for these joints (Fig 5). Subjects
489 used more similar synergies during the CC than during the PC (Fig. 6A). The conjoint synergies
490 were less similar than expected by chance when comparing the control and precision conditions
491 (Fig. 7B). These two results show that a change in inter-joint moments coordination occurred
492 due to the precision constraint. The synergies appeared more variable during the precision
493 condition (Fig 5) and the weighting coefficients were “shared” between participants during the
494 precision condition, e.g., the wrist joint moment for subject #2 was loaded with the wrist, elbow,
495 and shoulder joint moment of subject #1 in the first conjoint synergy (Fig. 7A). These results
496 suggest that although the coordination was more variable during the precision condition more
497 co-variation occurred between the joint moments of the two participants. These results show
498 that the collaboration during the precision task required disorganization of the spontaneous
499 coordination adopted by the participants when no precision constraint was present. The change
500 in posture between CC and PC might partly explain this observation. The VAF for the conjoint

501 analysis tended to be lower during the precision condition (i.e., $p=0.06$) also suggesting a more
502 variable coordination pattern between the joint moments of the two participants. These results
503 suggest that coordinated action between two subjects does not necessarily require a similar
504 coordination pattern for each of them, i.e., similar dynamic synergies, and that, in our
505 experiments, a new coordination pattern emerged between the two subjects (i.e., different joint
506 synergies), with more co-variation between their joint moments.

507 Our study highlights the fact that, when a dyad of individuals collectively transports a load and
508 performs a second task (requiring accuracy and precision), the displacement of the CoM of the
509 whole system (PACS) is affected, inducing a less efficient pendulum-like behavior. In both
510 conditions the individuals coordinated their forces to move in the vertical and forward direction
511 without adopting a common strategy in the left-right direction. We also observed that the
512 individuals changed their trunk orientation and their behavior to manage the displacement of
513 the ball inside the target. Furthermore, the visual feed-back permitted the dyad to coordinate
514 their forces and movements in order to better control the position of the ball. However, the
515 kinetic synergy analysis showed that subjects altered the structure of their own synergies in PC
516 to adopt a coordination that was dissimilar between subjects but in which their wrist joint
517 moments co-varied more. These results could be of interest for people working in ergonomics
518 and could find potential developments in robotics (e.g. human-robot interactions), and in the
519 rehabilitation domain, for example, when several caregivers in health care establishments have
520 to move a patient.

521 **6 List of symbols and abbreviations**

522 **CC:** Control condition

523 **CoM:** Center of mass

524 **CI:** Confidence Interval

525 **MCF:** Moment Cost Function

526 **PACS:** Poly-Articulated Collective System

527 **PC:** Precision Condition

528 **PCA:** Pincipal Component Analysis

529 **RR:** Recovery Rate

530 **VAF:** Variance Accounted For

531 **7 Author contributions**

532 NS: responsible for the data analysis, interpretation and manuscript writing. GF: responsible for
533 the data analysis and interpretation, and major revisions of the manuscript. VF: responsible for
534 the study design, supervision, data interpretation and major revisions of the manuscript. NAT:
535 responsible for the data analysis and interpretation and major revisions of the manuscript. PM:
536 Responsible for the study design, supervision, data interpretation and major revisions of the
537 manuscript.

538 **8 Competing interests**

539 The authors do not have to disclose any financial or personal relationships with other people or
540 organizations that could inappropriately influence (bias) their work.

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545

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673 **11 Figure legends**

674 **Figure 1. Experimental setup: Collective load carriage performed with a precision task**
675 **(PC).** The dyad carried a box (mass = 13.41 kg, size: 0.40x 0.40 x 0.28) while maintaining a
676 ball (diameter=19mm, mass=2g) in the center of a targeted position (diameter of the small and
677 large circle: 120 mm and 240 mm respectively) on its top. If the ball was maintained in the
678 small circle, the dyad obtained a 1-point Score_p. If it was maintained between the small and
679 large circle, then they obtained 0,5-point Score_p. Else, they obtained 0-point Score_p.

680

681 **Figure 2. Amplitude (A) and period (B) of the vertical displacement of the CoM_{PACS} in the**
682 **Control Condition (CC) and the Precision Condition (PC).** The mean value of each dyad
683 (N=10) was computed for the CC and PC and linked. The red points represent the mean for
684 each condition. The same color is assigned to each dyad in all figures. * = significant difference
685 (p<0.05 paired t-test).

686

687 **Figure 3. Recovery Rate (%) of each dyad (N=10) during Control Condition (CC) and**
688 **Precision Condition (PC).** The red points represent the mean for each condition. The same
689 color is assigned to each dyad in all figures. * = significant difference (p<0.05 paired t-test).

690

691 **Figure 4. Boxes plot showing the distribution of the correlation coefficient (Coef). A :** Coef
692 of the forces produced by the individuals in each dyad on the box handles, on the medio-lateral
693 (Fx), antero-posterior (Fy) and vertical axis (Fz) in the CC and PC conditions. B : Coef of the
694 ball displacement and the handles displacement, on Fx, Fy, and Fz, in the CC and PC conditions.
695 C : Coef of the ball trajectory and the sum of forces exerted by the subjects on the handles, on
696 Fx, Fy, and Fz, in PC. N = 10 for each condition. * 0.05> p> 0.01; ** p <0.01 (paired Student
697 t test). The upper horizontal line of the box represents the third quartile (75th percentile), the
698 lower line of the box represent the first quartile (25th percentile), the middle value of the dataset
699 is the median value (50th percentile) and the upper and lower horizontal lines outside the box
700 represent respectively 90th percentile and 10th percentile. Cross-and circle represent
701 respectively outlier and mean.

702

703 **Figure 5. Dynamic synergy vectors.** Three synergies accounted for more than 90.0% of total
704 variance in all subjects and conditions. Participants labeled #1 were on the right side of the load
705 and participants #2 on the left side. Wrist, elbow and shoulder were abbreviated to wr. el. and
706 sh. respectively. R and L refer to right and left side, respectively.

707

708 **Figure 6. Subspaces comparison.** The subspace angle measures the similarity between the
709 subspaces spanned by the dynamic synergies. The 95%-confidence interval of angles obtained
710 with random synergies (95%-CI chance) is indicated, i.e., CI=[49.5°,70.0°]. the star (*)
711 indicates a significant difference (i.e., $p < 0.001$).

712

713 **Figure 7. Conjoint synergies.** S1 and S2 refer to participants #1 (right side) and participant #2
714 (left side), respectively. The 95%-confidence interval of angles obtained with random synergies
715 (95%-CI chance) is indicated in panel B, i.e., CI=[36.3°,79.1°].

716 **12 Tables**

Group	Control Condition			Precision Condition		
	LagX	LagY	LagZ	LagX	LagY	LagZ
1	0	0	0	0	0	0,155 *
2	0	0	0,04	0	0	0,56 *
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0,15 *
7	0	0	0,15 *	0	0	0
8	0	0	0	0	0	0,355 *
9	0	0	0	0	0	0
10	0	0	0	0	0	0,545 *

717 **Table 1. The action-reaction strategy**, the time lag (s) required for the position of the left side
 718 and right side of the box to be the same on the medio-lateral, antero-posterior and vertical axis
 719 in CC and PC. * **150 ms < p (VanRullen and Thorpe,2001)**

720

	CC	S.D	PC	S.D
Head orientation	2.58	± 4.61	60.00 **	± 11.81
Shoulders orientation	1.99	± 3.13	11.21 **	± 6.61
Pelvis orientation	0.16	± 5.14	3.45 *	± 4.05
Distance FOR-STE	21.67	± 4.86	13.98 **	± 3.25

721 **Table 2. Head, shoulders and pelvis orientation (angles in degrees) and distance between**
 722 **the forehead and the sternum (FOR-STE, in centimeters) in the CC and PC conditions;**
 723 **mean (± s.d.). N=20 for each condition. * 0.05 > p > 0.01; ** p < 0.01 (paired Student t test).**

724