

The impact of collective load transport on individual walking

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1 Abstract

Collective handling is a collaborative strategy that involves two or more people in carrying out load transport. Different positions can be adopted, depending on the handle locations of the transported load, external constraints, and the capacities of the carriers. The most commonly used collective transport in our daily life is stretcher-type transport. Yet, very little research has focused on the kinematic modifications caused by this type of transport. This research aims to evaluate and quantify the modifications of the locomotor pattern of stretcher transport. Our results highlighted a modification of walking parameters (step length, duration of the walking cycle, speed of execution, etc.), an increase in energy cost, but above all a modification of the walking pattern with a reduction in joint range of motion. These results could be used to establish new recommendations for musculoskeletal disorders.

2 Introduction

Team lifting is a collaborative strategy that involves two persons or more in the transport of a load. Various configurations can be found in real life situations, with various placements

20 of the hand on the object, various external constraints (*e.g.*, weight of the object, corridors),
21 and the various capacities and preferences of the carriers (Barrett & Dennis, 2005). These
22 parameters have been studied to some extent in the scientific literature, although mainly for
23 single carriers. For example, researchers studied the optimal box handle positions that could
24 increase user satisfaction during individual manual handling (Jung & Jung, 2010). Load
25 characteristics such as shape and dimension were shown to play an important role in the
26 ability to comfortably carry weight (Garg & Saxena, 1980). In 1981, The National Institute
27 for Occupational Safety and Health (NIOSH) established an ergonomic equation evaluating
28 weight limits for lifting tasks for single individuals. This takes into consideration the vertical
29 location of the load, the distance the load is lifted, the frequency of lifting, and the symmetric
30 or non-symmetric aspect of the lifting. There is nevertheless a lack of information to provide
31 clear instructions about how to lift a load in a collective configuration.

32 So far, it is individual lifting that has been studied mainly (Datta & Ramanathan, 1971;
33 Heglund *et al.*, 1995). According to these researches, the best way to carry a load
34 individually, in terms of ergonomics, is to use the double pack mode and the head mode. In
35 contrast, carrying the load by hand was the worst method to transport a load. These data
36 mainly suggested that the load should be as aligned as possible with the center of mass of the
37 subjects to avoid creating a destabilizing torque. However, the ergonomic evaluations were
38 only based on physiological parameters such as oxygen consumption and heart rate.

39 The collective aspect of lifting has received much less attention and is more often studied
40 for practical/applied cases such as observed in health care facilities (Haiduven, 2003; Barrett
41 & Dennis, 2005), construction workers (Faber *et al.*, 2012; van der Molen *et al.*, 2012; Anton,
42 Mizner & Hess, 2013), rescue (Gamble *et al.*, 1991) or military activities (Sharp *et al.*, 1997;
43 Knapik, Reynolds & Harman, 2004). Transporting a casualty on a stretcher is commonly
44 studied by research in order to evaluate individual performance and hand-grip-strength

45 recovery (Knapik, Harper & Crowell, 1999; Leyk *et al.*, 2006, 2007). Armstrong *et al.* (2020)
46 ranked paramedic lifting task using a measure of biomechanical exposure and showed that the
47 worst activity while working was lifting a scoop board from the ground to the waist.
48 Moreover, they showed that the position of the carrier, head or foot end of the equipment,
49 didn't modify the biomechanical exposure.

50 Few biomechanically based investigations of collective stretcher transport have been
51 conducted. Lanini *et al.* (2017) studied human walking gait kinematics adaptations during
52 load transport and considered it as a quadrupedal gait. The results showed an overall
53 modification in gait parameters such as step length, gait cycle time, and Center of Mass
54 vertical displacement associated to a walking gait synchronization of the participant. Sensory
55 and tactile feedback in human walking helps dyads to synchronize their movements during
56 side-by-side walking (Nessler & Gilliland, 2009; Zivotofsky, Gruendlinger & Hausdorff,
57 2012; Sylos-Labini *et al.*, 2018; Felsberg & Rhea, 2021). Fumery *et al.* (2018), studied the
58 walking efficiency during a side-by-side collective load transport, and showed the ability of
59 humans to collaborate efficiently during load carriage. However, all of these researches
60 focused more on the collective modifications during a load transport and not on how the
61 collective tasks impacted the individual performance. This collective movement could be
62 mainly performed in two ways: (1) team members look at each other and (2) they look in the
63 same direction to transport a load. The first technique implies that one member walks
64 forwards while the other walks backwards, which could play a major role in the individual
65 and collective performance of the load transport. For now, most of the researches described
66 the backwards walking pattern as a simple kinematic time reversal of the forwards walking
67 pattern and reported only few differences (Thorstensson, 1986; Winter, Pluck & Yang, 1989;
68 Lee *et al.*, 2013). However, backwards walking in a collective transport task has not been
69 investigated.

70 In this research we looked forwards to exploring different aspects of a collective stretcher
71 transport, and more specially how this kind of transport impacts the biomechanical individual
72 behavior. The objective of this research is to address three scientific questions: (1) What are
73 the differences between forwards and backwards walking? (2). How does collective load
74 transport impact the biomechanics of individuals walking forwards?, and (3) How does
75 collective transport impact backwards walking when participants are facing each other ?

76 **3 Materials and methods**

77 **3.1 Population**

78 Twelve women and eight men participated in this research. All participants were free of
79 musculoskeletal or neurological disorder that might have affected the carriage. Mean (\pm s.d.)
80 age, height, and body weight were $24 \pm 2,6$ years, $1,71 \pm 0,07$ m and $64,65 \pm 8$ kg,
81 respectively. Each duo was matched by gender, height and weight. The project was approved
82 by the University Review Board and all participants gave their written and oral consent in
83 accordance with the Helsinki Convention.

84 **3.2 Experimental setup**

85 In total, 10 dyads performed four different lifting conditions. For the first two conditions,
86 the participants were given the instruction to walk individually at their own pace in a forwards
87 direction (C1) and in a backwards direction (C2), over a distance of 13 m. Then two collective
88 conditions consisted in collectively transporting a stretcher-shaped load of 1.2 kg with
89 participant 1 at the front and participant 2 at the back (Figure 1.c). We instructed the
90 participants to transport the stretcher-shaped load while looking in the same direction (Figure

91 1.d) over a distance of 13 m; meaning that both participants were performing a forwards
92 walking (C3). And we instructed them to perform the same condition while looking at each
93 other (Figure 1.e); meaning that participant 1 was performing a backwards walking and
94 participant 2 was performing a forwards walking (C4). All conditions were randomly
95 presented, as the position of the participant (in front or at the back). Three trials were recorded
96 in each condition.

97 **Figure 1: Experimental protocol with the placement of the participants for conditions 1 (a),**
98 **condition 2 (b), condition 3 (d), and condition 4 (e). With (c) representing the top view of the**
99 **stretcher-shaped load.**

100 **3.3 Kinematic data acquisition**

101 Motion capture data were collected using 20 infrareds (11 Vero V2.2, 7 MX3 and 2 MX
102 TS40) transmitter-receiver video cameras (Vicon, Oxford metric's, Oxford, United Kingdom)
103 sampled at 200 Hz. Forty-two retro-reflective markers were placed on bony landmarks and on
104 the navel of each participant (Wu *et al.*, 2002, 2005), and thirteen on the stretcher-shaped
105 load. One gait cycle per trial and participant has been considered for the analysis. These
106 cycles were selected close to the middle of the travel path to avoid acceleration and
107 deceleration phases. The gait cycle of walking was defined by two successive foot strikes of
108 the same foot. Regarding the collective transport C3 and C4, we investigated the gait cycle of
109 the Poly-Articulated Collective System (PACS) formed by the two participants and the load
110 they carry. It started with the first heel strike of participant 2 (at the back) and ended with the
111 second foot strike of participant 1 (at the front). The three-dimensional reconstruction of the
112 markers position was performed using the Vicon Nexus 2.11.0 software.

113 3.4 Computed parameters

114 3.4.1 Gait parameters

115 **Step length** (SL) was computed as the distance travelled between the foot strike of one
116 foot and the strike of the contralateral foot.

117 **Gait Cycle Time** (GCT) was computed as the time between two consecutive foot strikes
118 of the same foot.

119 3.4.2 CoM trajectory

120 De Leva anthropometric table (1996) was used to estimate the masses of each segment
121 (m_i), the position of the center of mass of each segment i (CoM_i) of the participants, and to
122 determine the global position of the CoM of each carrier (i.e. $CoM_{Participant1}$, $CoM_{Participant2}$).
123 They were then use to define the PACS CoM (CoM_{PACS}). The participants and PACS CoM
124 location were all computed in the global frame of reference $R(0, x, y, z)$ as follows
125 ($m_{Participant1/2}$, Participant 1 or 2 mass; m_{PACS} , PACS mass) :

$$\overrightarrow{OCOM}_{Participant1/2} = \frac{1}{m_{Participant1/2}} \sum_{i=1}^{n=16} m_i \overrightarrow{OCOM}_i$$

$$\overrightarrow{OCOM}_{PACS} = \frac{1}{m_{PACS}} \sum_{i=1}^{n=33} m_i \overrightarrow{OCOM}_i$$

126 We then assessed the vertical amplitude ($A = Z_{max} - Z_{min}$, with Z the CoM height), the
127 CoM period (P) referring to the time between two peaks of the z -position curve, and the CoM
128 Velocity (Winter, 2009).

129 **3.4.3 Recovery rate**

130 The Recovery Rate (RR) assesses the amount of energy transferred between the potential
131 and the kinetic energy of the center of mass (Bastien *et al.*, 2016; Fumery *et al.*, 2018a;
132 Sghaier *et al.*, 2022). The RR is related to the consistency of the locomotor pattern and is
133 based on the analysis of an inverted pendulum system (IPS) (Cavagna, Saibene & Margaria,
134 1963; Willems, Cavagna & Heglund, 1995; Gomeñuka *et al.*, 2014). RR was computed for
135 each participant and the PACS as follow:

$$RR = 100 \frac{W_{kf} + W_v - W_{ext}}{W_{kf} + W_v}$$

136 With W_{kf} work performed in the forwards direction, W_v the vertical work and W_{ext} the
137 external work. These parameters were computed according to the method of Bastien *et al.*
138 (2016).

139 **3.4.4 Joint angles**

140 In order to study the kinematic modifications during a walking and a transporting task,
141 we computed the joint angles at the hip, knee, and ankle joints during a complete gait cycle.
142 These joint kinematics were calculated according to the method proposed by the
143 “Standardization and Terminology Committee” of the ISB, which defines a set of coordinate
144 systems for various joints of the lower body based on the joint coordinate system and the
145 XYZ sequence (Wu & Cavanagh, 1995; Wu *et al.*, 2002).

146 The flexion/extension joint angles of the hip, knee and ankle were computed for each
147 participant and condition in order to highlight gait modification. According to Winter *et al.*,
148 (1989), the angles to time curve have been reversed from 100% to 0% of the gait cycle to
149 compare backwards to forwards walking.

150 **3.5 Statistical analysis**

151 Statistical analysis was performed with the software R v4.0.2 (<http://www.r-project.org/>).

152 We compared CoM velocity, step length, GCT, RR, CoM period and CoM amplitude across

153 the four experimental conditions (C1, C2, C3, and C4) using linear mixed model approach.

154 We then estimated marginal means for each condition using the package *emmeans* in R

155 (Searle, Speed & Milliken, 1980; Lenth *et al.*, 2023; [https://CRAN.R-](https://CRAN.R-project.org/package=emmeans)

156 [project.org/package=emmeans](https://CRAN.R-project.org/package=emmeans)). In order to analyze joint angle evolution, we used the Laassel

157 *et al.* (1992) method. The gait cycle was divided into 25 windows, each of 4% of the gait time

158 duration. To evaluate the effect of backwards walking on the individual and collective

159 walking, we ran 6 different linear models for each participant (P1 and P2) and each joints

160 (hip, knee and ankle). Each model was built using conditions, windows and their interaction

161 as predictors and angles as response variable. We then estimated the angle marginal means

162 and their confidence interval for each condition in each window using the package *emmeans*

163 in R.

164

165 **4 Results**

166 **4.1 Gait parameters**

167 The step length of participant 1 was significantly longer for C1 compared to C2

168 (respectively by +20.5% and +26.1%), C3 (respectively by 7.8% and 9.1%) and C4

169 (respectively by 19.6% and 14.9%). These differences were of +16% between C2 and C3

170 (C2>C3) and +12.8% between C3 and C4 (Figure 2.a). As for the second participant, step

171 lengths during C2 were significantly shorter than those performed during C1 (-35.3%), C3 (-
172 22.9%) and C4 (-15.1%).

173 **Figure 2: Step length and Gait Cycle time boxplot for participant 1 respectively (a), (c) and**
174 **participant 2 (b) and (d) for condition 1,2, 3 and, 4. Light grey boxplots represent the forward**
175 **walking performance and, dark grey boxplots represent the backward walking performance(***
176 **p< 0,05; ** p<0,01 and; *** p<0,001).**

177 Globally the GCT of participant 1 was stable across the different conditions. However,
178 Participant 2 GCT was 7% greater in the collective conditions (C3, C4) than in the individual
179 conditions (C1, C2). In addition, the GCT of C4 was 4.3% longer than the one of C3 (Figure
180 2.d).

181 **4.2 Center of Mass (CoM) excursion**

182 In order to compare the evolution of the CoM vertical excursion during a gait cycle
183 (Figure 3), we computed the mean CoM amplitude and the CoM period for each trial (Figure
184 3). No differences were found for the individual CoM vertical excursion of P1 or P2 across
185 the different conditions (Figure 3,a,c). However, the mean P1 and P2 CoM amplitude showed
186 a 17.2% higher amplitude during forward walking C1 than during backward walking C2
187 (Figure 3,b). In addition, PACS's CoM excursion was also 45.2% significantly higher in C3
188 than in C4 (Figure 3,d). Concerning the CoM period, all conditions were the same whether
189 they were performed individually or collectively.

190 **Figure 3 : Center of Mass mean vertical excursion (10^{-2}) for participant 1 (a) and (b), participant**
191 **2 (b) and (c) and, PACS (d). Continuous lines represent the individual conditions C1 and C2 and,**
192 **the dashed lines represent the collective conditions C3 and C4. The black line correspond to the**
193 **forward walking performance and, the blue ones to the backward walking performance.**

194 4.3 CoM velocity

195 The P1 and P2 velocities performed in C1 decreased by 23.1% in C2, by 11.4 in C3 and
196 by 20.15% in C4 (Figure 4.a,c).

197 Forward walking appears always faster than backward walking whether the participants
198 are linked or not. Indeed, P1 and P2 increased their walking speed by 13.6% and 16.7% from
199 C2 to C3. This is confirmed from C3 to C4 with a mean decrease of 10% for P1 and P2.
200 Individually, backward walking induces a 23% decrease of the velocity (Figure 4.b). It is
201 confirmed when the participants carry the load. The velocity of the PACS during C3
202 decreased by 9.9% compared to the one computed for C4 (Figure 4.d).

203 **Figure 4 : Center of Mass velocity ($m.s^{-1}$) boxplots for participant 1 (a) and (b), participant 2 (c)**
204 **and (b) and, PACS (d). for condition 1,2, 3 and, 4. Light grey boxplots represent the forward**
205 **walking performance and, dark grey boxplots represent the backward walking performance(***
206 **$p < 0,05$; ** $p < 0,01$ and; *** $p < 0,001$).**

207 4.4 Recovery rate

208 Concerning P1, statistical analysis showed a significant decrease of the RR by 38.8%
209 from C1 to C2 and, and then by 44.3% from C3 to C4 (Figure 5.a). P2 RR significantly
210 decrease across C1 and C2, C1 and C3 then C1 and C4 by 73.6%, 55.7% and, 43.9%,
211 respectively. In addition, a P2 diminution of 10.3% from C1 to C3 and, a diminution of 17.1%
212 from C1 to C4 were observed (Figure 5.c). Individually, the RR of forward walking C1
213 decreased by 40.7% compared to backward walking C2 (Figure 5.b). In parallel, the RR
214 computed for the PACS during C3 also decreased by 27.5% compared to C4 (Figure 5.d).

215

216 **Figure 5 :Recovery Rate (%) boxplots for participant 1 (a) and (b), participant 2 (c) and (b) and,**
217 **PACS (d). for condition 1,2, 3 and, 4. Light grey boxplots represent the forward walking**
218 **performance and, dark grey boxplots represent the backward walking performance (* p< 0,05;**
219 **** p<0,01 and; *** p<0,001).**

220 **4.5 Joint angles (Hip- Knee-Ankle)**

221 For the participant 1, two different strategies were used depending on the walk performed
222 (forward or backward walking). A higher flexion at the initial heel strike was observed during
223 forward walking for participant 1. Differences were found between 40% and 80% of the gait
224 cycle, with a decrease of 8° on average for the hip extension angle between C1 and C3
225 (forward walking) and between C2 and C4 (backward walking). Besides, the terminal stance
226 occurred 8% later in backward walking compared to forward walking. The terminal stance of
227 C1 and C3 occurred around 55% of the gait cycle, while, for C2 and C4 it occurred earlier
228 (48% of the gait cycle). The same goes for the terminal swing, which was occurring in the
229 early 80% of the gait cycle in the C2 and C4, whereas, it was occurring at 90% of the gait
230 cycle in C1 and C3.

231 **Figure 6 : Participant 1 hip flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
232 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 and C3 curves are**
233 **reversed in time.**

234 Concerning the participant 2, no difference was found across C1, C3 and C4. However,
235 as observed in the participant 1, a 23.6% decrease of the initial angle at heel strike has been
236 observed from forward to backward walking. We also found a 140.3% (9°) decrease of hip
237 extension across forward walking (C1, C3 and, C4) and backward walking (C2) at 60% of the
238 gait cycle.

239 **Figure 7 : Participant 2 hip flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
240 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 curve is reversed**
241 **in time.**

242 As for the hip, two strategies of flexion/extension occurred during the forward and
243 backward walking. C1 and C3 represent a normal forward walking, with two
244 flexion/extension peaks, one at 15% of the cycle and another one at 75% of the cycle.
245 Conversely, the reversed results of backward walking, showed an erasure of the first peak
246 associated to a direct increase of the knee flexion from 30% to 60% of the gait cycle. There
247 was also a delay for the second peak which was occurring at 65% of the cycle. Besides, a 7°
248 decrease of the second peak amplitude has been observed.

249 **Figure 8 : Participant 1 knee flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
250 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 and C3 curves are**
251 **reversed in time.**

252 Participant 2 developed the same joint kinematic strategies as demonstrated at the three
253 joints and in the three conditions (C1, C3 and, C4).

254 **Figure 9 : Participant 2 knee flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
255 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 curve is reversed**
256 **in time.**

257 The results of ankle dorsi/plantar flexion reveal an increase of the dorsiflexion during C2
258 and C4, by 27.1% and 56.5% at 36% of the cycle, respectively. At the initial swing phase, the
259 plantar flexion reached 12° in C3 and 9° in C1 at 65% of the cycle, while, the ankle joint
260 reached a plantar flexion limited to approximatively 7° at 92% of the cycle. Besides, the

261 plantar flexion was 95.3% higher in C4 collective performance than for the C2 individual
262 performance.

263 **Figure 10 : Participant 1 ankle flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
264 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 and C3 curves are**
265 **reversed in time.**

266 The same results were observed in the participant 2, when comparing the C2 angles to the
267 three other conditions (C1, C3 and, C4).

268 **Figure 11 : Participant 2 ankle flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**
269 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 curves is reversed**
270 **in time.**

271 **5 Discussion**

272 The purpose of this study was to investigate how a collective task such as stretcher
273 transport influences individual walking patterns. We used two load transport configurations
274 with subjects looking in the same direction or in opposite directions while transporting the
275 load, and compared the collective walking pattern with individual walking pattern without
276 load. We studied the differences across forwards and backwards walking, compared
277 individual walking to linked walking, and studied the impact of backwards walking on linked
278 walking. The results showed that the collective task modifies the spontaneous walking
279 pattern, but for one participant mainly.

280 We first compared the spatiotemporal parameters when performing forwards walking and
281 backwards walking. According to Fritz *et al.*, (2013) and Lee *et al.*, (2013), a reduction of the

282 step length and the CoM velocity during condition 2 was observed. The velocity of walking
283 velocity depends on step length (JudgeRoy, Davis & Ounpuu, 1996). Unlike forwards
284 walking C1, backwards walking C2 is occasionally used in the human range of motion even if
285 it alters the movement efficiency. In addition, we instructed the participants to look straight
286 ahead during C2 meaning there was an absence of visual feedback. Studies explained that in
287 order to reduce their subjective instability, participants had to reduce their step length as well
288 as their speed (Grasso, Bianchi & Lacquaniti, 1998). Besides, the diminution of the average
289 range of the hip flexion/extension induced the diminution of step length parameters (Perry, K
290 & Davids, 1992). These results, though, did not impact the gait cycle time, which was
291 globally around 1 second for both conditions.

292 The RR was used as an indicator of the efficiency of the walking pattern, with the
293 objective to assess the amount of energy transferred between the potential and the kinetic
294 energy due to a pendulum-like behavior. Globally, RR was always significantly higher when
295 the participant performed forwards rather than backwards, whether in individual or collective
296 condition. The results obtained for individual forwards C1 and backwards C2 walking were
297 close to the values found in literature (Minetti & Ardigò, 2001). This same research states that
298 this diminution can be explained by a loss of energy, which occurs when the duty factor (the
299 proportion of ground contact reported to the stride) approaches 50% of the gait cycle, thus
300 reducing the double-contact time. Concerning the collective conditions, our results were close
301 to those obtained by Fumery *et al.* (2021).

302 The vertical Center of Mass (CoM) excursion has been widely for normal and
303 pathological walking. However, very few described what happens when walking backwards,
304 even less so when transport was collective. Our main result showed a diminution of CoM
305 amplitude across individual walking, forwards and backwards, which can be explained by
306 velocity decrease and limitation of movement. This limitation occurs mainly at the terminal

307 stance (50% of the gait cycle). In fact, as far as forwards walking is concerned the hip
308 extension reaches 10°, whereas when it is backwards the hip extension is not present.

309 Most of the research done on backwards walking considered it as the reverse of normal
310 forwards walking (Thorstensson, 1986; Winter *et al.*, 1989; Lee *et al.*, 2013). In this study, we
311 compared the results of forwards walking to the reverse of those of backwards walking. It
312 showed, as stated by the literature, a more or less similar time-reversed pattern of
313 flexion/extension at the hip, knee, and ankle. In order to compare the range of motion
314 evolution, Lee *et al.* (2013) compared only the maximum flexion/extension angles during
315 selected crucial joint points: loading response, stance, and swing phase. In this study we
316 performed a sliding window of 4% to see joint angles evolution during a complete
317 flexion/extension cycle. This statistical analysis enabled us to analyze how backwards
318 walking (C2) impacted gait pattern. It reveals a decrease of the range of motion and an early
319 occurrence of some crucial points. The results showed a clear diminution of the extension for
320 both participants when performing backwards walking (C2). This result could also explain the
321 early occurrence of the final stance, around 48% of the gait cycle. The knee flexion/extension
322 was also impacted by backwards walking (C2) with a decrease of the knee flexion at 80% of
323 the gait cycle. The results obtained for the ankle correspond to those of Balasukumaran *et al.*
324 (2020), who demonstrated a modification of the walking pattern kinematics. Our results
325 confirm in some ways that backwards walking (C2) is a kinematic reversal of forwards
326 walking (Winter *et al.*, 1989). However, we found major modifications in joint angle
327 amplitudes and a delay of the occurrence of some crucial time points. Those modifications
328 can clearly explain the spatiotemporal parameters decrease (step length, velocity and RR).

329 Concerning the collective transport, we recorded two conditions where the main
330 difference was the position of participant 1. In the C3 collective condition, both participants
331 looked in the same direction. The results obtained showed that both participants reduced their

332 speed when transporting the load. Multiple research showed that during individual walking,
333 when load weight tends to increase, spontaneous velocity tends to decrease due to step length
334 reduction (James *et al.*, 2015). These modifications allow humans to spontaneously adopt an
335 optimal gait and walking speed to minimize the energetic cost (Minetti & Alexander, 1997;
336 Bode *et al.*, 2021). However, in our study, we opted for a light transported object to focus on
337 the effect of a physical link across the participants. This means that the observed
338 modifications were only due to the physical link that induced the first step of a collaborative
339 task.

340 These diminutions are amplified during C4, where participants looked at each other while
341 transporting the stretcher-like-object. Indeed, the individual performance of P1 showed an
342 increase of backwards velocity during C4 compared to C2, when P2, on the contrary,
343 decreased their forwards velocity in C4 compared to performance in C1 and C3. Regarding
344 Gait Cycle Time CGT during the different conditions, P2 were the ones who modified their
345 timing depending on the performed tasks. Lanini *et al.*(2017), explained that global gait
346 adaptations are mainly due to the fact that each subject tries to accommodate to the motion of
347 the other subject, which is detected by interaction forces, visual and acoustic information.
348 During the experiments, the participants unintentionally communicated through the
349 interaction forces, that are considered as sensory feed-back (Zivotofsky *et al.* 2012).

350 For P1, the collective load transport did not impact his RR performance, and no
351 difference was found across individuals and collective performance for forwards and
352 backwards walking. Whereas, P2 constantly modified their behavior depending on the
353 condition. P2 RR decreased while performing C3, and even more so when C4 was performed.
354 Fumery *et al.*(2018b) studied paired walking of adults with intellectual disabilities and
355 showed that when the participant is paired to a healthy individual, there is an improvement of
356 spatiotemporal of the disabled participant and a decrease of the healthy participant pattern. In

357 our study it seems that P2 plays an important role in the constant kinematic readjustment due
358 to the increase in environment inputs, and given the fact that backwards walking disturbed P1
359 efficiency.

360 Concerning kinematic modifications, the collective load transport C3 slightly impacted
361 the kinematics of participant 1 gait pattern in hip flexion/extension at the beginning and the
362 end of the cycle. However, no other kinematic modification has been noticed for the other
363 joint, as well as for participant 2. In general, the major modifications induced by a collective
364 load transport are those found in spatiotemporal parameters.

365 The objective of condition C4 was to see if the backwards walking performed by
366 participant 2 impacted the kinematic individual performance of participant 1 as well as the
367 collective performance. Kinematic results of participant 1 showed higher flexion values for
368 each of the hip, knee, and ankle when comparing the individual backwards performance C2.
369 On the contrary, no kinematic modifications were found for participant 2.

370 Regarding the dyad performance, we focused on the Poly-Articulated Collective System
371 (PACS) formed by the two participants and the load they transported. As done for the
372 participants, we computed the PACS velocity and RR, with the purpose to bring out how P1
373 placement impacted the collective performance. Both collective conditions replicate two types
374 of collective stretcher transport. Our results showed a velocity decrease of the PACS from C3
375 to C4. This can be explained by the velocity individual decrease of each participant. The RR
376 also decreased by 10% from C3 to C4. These two results join those found by Sghaier *et al.*
377 (2022), who studied a collective side-by-side load transport associated to a precision
378 constraint, and showed a decrease of the PACS velocity and RR. The amplitude of the CoM
379 displacement also showed a decrease from C3 to C4. These results illustrate a better collective
380 efficiency for C3, meaning when both participants performed forwards walking while looking
381 in the same direction. This also means that backwards walking during collective transport

382 affects the efficiency of the collective work. To remedy this efficiency loss, it would be
383 interesting to use different lifting aids such as passive exoskeleton. Indeed, it has been shown
384 that exoskeletons enhance operators' capacities without modifying their kinematic pattern
385 (Sghaier *et al.*, 2019). Future research should study the impact of exoskeletons on collective
386 transport.

387 Conclusion

388 The present study gives insight into how collective load transport modifies the individual
389 walking performance. We first compared individual forwards and backwards walking. As
390 stated in the literature we observed a kinematic time reversal of the flexion/extension angles.
391 However, we observed major modifications in the flexion/extension amplitude and a delay of
392 the occurrence of some crucial time points inducing a modification of some spatiotemporal
393 parameters. Then we studied the impact of collective load transport on individual walking
394 performances. When participants looked in the same direction, we observed a slight kinematic
395 modification. Yet, the linked task induced a decrease of spatiotemporal parameters. However,
396 when participants looked at each other during the carriage, we observed higher flexion values
397 for participant 1, in addition to the decrease of spatiotemporal parameters. The efficiency of
398 the collaborative task decreased when participant looked at each other as shown by the
399 decrease of the RR. This result indicates that the component impacting most on the efficiency
400 of a collective load transport was the performance of a backwards walking by participant 1.
401 Moreover, the efficiency of the collaborative task was mainly controlled by participant 2 with
402 more environment information. The latter systematically adjusted their behavior
403 (spatiotemporal parameter) in order to adapt to the other participant who was performing
404 backwards walking. Future research should study the forces interacting across participants in
405 order to understand the involvement of each participant.

406 6 References

- 407 1. Barrett R s., Dennis G j. Ergonomic issues in team lifting. *Human Factors and Ergonomics*
408 in *Manufacturing & Service Industries*. 2005;15(3):293–307.
- 409 2. Jung HS, Jung HS. A survey of the optimal handle position for boxes with different sizes
410 and manual handling positions. *Applied Ergonomics*. 2010 Jan 1;41(1):115–22.
- 411 3. Garg A, Saxena U. Container Characteristics and Maximum Acceptable Weight of Lift.
412 *Hum Factors*. 1980 Aug 1;22(4):487–95.
- 413 4. Datta SR, Ramanathan NL. Ergonomic Comparison of Seven Modes of Carrying Loads on
414 the Horizontal Plane. *Ergonomics*. 1971 Mar;14(2):269–78.
- 415 5. Heglund NC, Willems PA, Penta M, Cavagna GA. Energy-saving gait mechanics with head-
416 supported loads. *Nature*. 1995 May 4;375(6526):52–4.
- 417 6. Haiduven D. Lifting Teams in Health Care Facilities: A Literature Review. *AAOHN*
418 *Journal*. 2003 May;51(5):210–8.
- 419 7. Faber G, Visser S, Van der Molen HF, Kuijter PPFM, Hoozemans MJM, Van Dieën JH, *et*
420 *al*. Does team lifting increase the variability in peak lumbar compression in ironworkers?
421 *Work*. 2012;41:4171–3.
- 422 8. van der Molen HF, Visser S, Kuijter PPFM, Faber G, Hoozemans MJM, van Dieën JH, *et al*.
423 The evaluation of team lifting on physical work demands and workload in ironworkers.
424 *Work*. 2012 Jan 1;41(Supplement 1):3771–3.
- 425 9. Anton D, Mizner RL, Hess JA. The Effect of Lift Teams on Kinematics and Muscle Activity
426 of the Upper Extremity and Trunk in Bricklayers. *Journal of Orthopaedic & Sports Physical*
427 *Therapy*. 2013 Apr;43(4):232–41.
- 428 10. Gamble RP, Stevens AB, McBrien H, Black A, Cran GW, Boreham CA. Physical fitness
429 and occupational demands of the Belfast ambulance service. *Occupational and*
430 *Environmental Medicine*. 1991 Sep 1;48(9):592–6.
- 431 11. Knapik JJ, Harper W, Crowell HP. Physiological factors in stretcher carriage performance.
432 *Eur J Appl Physiol*. 1999 Mar 1;79(5):409–13.

- 433 12. Leyk D, Rohde U, Erley O, Gorges W, Wunderlich M, Rütther T, et al. Recovery of hand
434 grip strength and hand steadiness after exhausting manual stretcher carriage. *Eur J Appl*
435 *Physiol.* 2006 Mar 1;96(5):593–9.
- 436 13. Leyk D, Rohde U, Erley O, Gorges W, Essfeld D, Erren TC, *et al.* Maximal manual stretcher
437 carriage: performance and recovery of male and female ambulance workers. *Ergonomics.*
438 2007 May;50(5):752–62.
- 439 14. Armstrong DP, Makhoul PJ, Sinden KE, Fischer SL. Ranking Stretcher and Backboard
440 Related Paramedic Lifting Tasks Based on Their Biomechanical Demand on the Low Back.
441 *IIE Transactions on Occupational Ergonomics and Human Factors.* 2020 Jan 2;8(1):9–19.
- 442 15. Lanini J, Duburcq A, Razavi H, Goff CGL, Ijspeert AJ. Interactive locomotion:
443 Investigation and modeling of physically-paired humans while walking. *PLOS ONE.* 2017
444 Sep 6;12(9):e0179989.
- 445 16. Nessler JA, Gilliland SJ. Interpersonal synchronization during side by side treadmill walking
446 is influenced by leg length differential and altered sensory feedback. *Human Movement*
447 *Science.* 2009 Dec 1;28(6):772–85.
- 448 17. Zivotofsky AZ, Gruendlinger L, Hausdorff JM. Modality-specific communication enabling
449 gait synchronization during over-ground side-by-side walking. *Human Movement Science.*
450 2012 Oct 1;31(5):1268–85.
- 451 18. Sylos-Labini F, d’Avella A, Lacquaniti F, Ivanenko Y. Human-Human Interaction Forces
452 and Interlimb Coordination During Side-by-Side Walking With Hand Contact. *Front*
453 *Physiol.* 2018 Mar 7;9:179.
- 454 19. Felsberg DT, Rhea CK. Spontaneous Interpersonal Synchronization of Gait: A Systematic
455 Review. *Archives of Rehabilitation Research and Clinical Translation.* 2021 Mar
456 1;3(1):100097.
- 457 20. Fumery G, Claverie L, Fourcassié V, Moretto P. Walking pattern efficiency during
458 collective load transport. *Gait & Posture.* 2018 Jul 1;64:244–7.
- 459 21. Thorstensson A. How is the normal locomotor program modified to produce walking? *Exp*
460 *Brain Res.* 1986 Feb 1;61(3):664–8.

- 461 22. Winter DA, Pluck N, Yang JF. Walking: A Simple Reversal of Walking? *Journal of Motor*
462 *Behavior*. 1989 Sep;21(3):291–305.
- 463 23. Lee M, Kim J, Son J, Kim Y. Kinematic and kinetic analysis during and walking. *Gait &*
464 *Posture*. 2013 Sep;38(4):674–8.
- 465 24. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation
466 on definitions of joint coordinate system of various joints for the reporting of human joint
467 motion—part I: ankle, hip, and spine. *Journal of Biomechanics*. 2002 Apr 1;35(4):543–8.
- 468 25. Wu G, Van der Helm FCT, (DirkJan) Veeger HEJ, Makhsoos M, Van Roy P, Anglin C, et
469 al. ISB recommendation on definitions of joint coordinate systems of various joints for the
470 reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of*
471 *Biomechanics*. 2005 May 1;38(5):981–92.
- 472 26. Winter D. *Biomechanics and Motor Control of Human Movement*. Hoboken : Wiley &
473 Sons, Incorporated, John ; 2009.
- 474 27. Bastien GJ, Willems PA, Schepens B, Heglund NC. The mechanics of head-supported load
475 carriage by Nepalese porters [Internet]. 2016 [cited 2020 Nov 20]. Available from:
476 <https://jeb.biologists.org/content/219/22/3626>
- 477 28. Sghaier N, Fumery G, Fourcassié V, Turpin NA, Moretto P. Biomechanical effects of the
478 addition of a precision constraint on a collective load carriage task. *R Soc open sci*. 2022
479 Aug;9(8):220636.
- 480 29. Cavagna GA, Saibene FP, Margaria R. External work in walking. *Journal of Applied*
481 *Physiology*. 1963 Jan 1;18(1):1–9.
- 482 30. Willems PA, Cavagna GA, Heglund NC. External, internal and total work in human
483 locomotion. *Journal of Experimental Biology*. 1995 Feb 1;198(2):379–93.
- 484 31. Gomeñuka NA, Bona RL, Rosa RG da, Peyré- Tartaruga LA. Adaptations to changing
485 speed, load, and gradient in human walking: Cost of transport, optimal speed, and pendulum.
486 *Scandinavian Journal of Medicine & Science in Sports*. 2014;24(3):e165–73.
- 487 32. Wu G, Cavanagh PR. ISB recommendations for standardization in the reporting of kinematic
488 data. *J Biomech*. 1995 Oct;28(10):1257–61.

- 489 33. Searle SR, Speed FM, Milliken GA. Population Marginal Means in the Linear Model: An
490 Alternative to Least Squares Means. *The American Statistician*. 1980 Nov;34(4):216–21.
- 491 34. Lenth RV, Bolker B, Buerkner P, Giné-Vázquez I, Herve M, Jung M, et al. emmeans:
492 Estimated Marginal Means, aka Least-Squares Means [Internet]. 2023 [cited 2023 Apr 19].
493 Available from: <https://CRAN.R-project.org/package=emmeans>
- 494 35. Laassel EM, Loslever P, Voisin PH, Herlant M. Analyse multidimensionnelle des forces de
495 réaction du pied au cours de la marche normale. *Acta Orthop Belg*. 1992;58(3):272–279.
- 496 36. Fritz NE, Worstell AM, Kloos AD, Siles AB, White SE, Kegelmeyer DA. walking
497 measures are sensitive to age-related changes in mobility and balance. *Gait & Posture*. 2013
498 Apr;37(4):593–7.
- 499 37. JudgeRoy JO, Davis B, Ounpuu S. Step Length Reductions in Advanced Age: The Role of
500 Ankle and Hip Kinetics. *The Journals of Gerontology Series A: Biological Sciences and*
501 *Medical Sciences*. 1996 Nov 1;51A(6):M303–12.
- 502 38. Grasso R, Bianchi L, Lacquaniti F. Motor Patterns for Human Gait: Versus Locomotion.
503 *Journal of Neurophysiology*. 1998 Oct 1;80(4):1868–85.
- 504 39. Perry J, K ST, Davids JR. Gait Analysis: Normal and Pathological Function. *Journal of*
505 *Pediatric Orthopaedics*. 1992 Dec;12(6):815.
- 506 40. Fumery G, Turpin NA, Claverie L, Fourcassié V, Moretto P. A biomechanical study of load
507 carriage by two paired subjects in response to increased load mass. *Scientific Reports*. 2021
508 Feb 23;11(1):4346.
- 509 41. Balasukumaran T, Gottlieb U, Springer S. Spatiotemporal gait characteristics and ankle
510 kinematics of walking in people with chronic ankle instability. *Sci Rep*. 2020 Jul
511 13;10(1):11515.
- 512 42. James CR, Atkins LT, Yang HS, Dufek JS, Bates BT. Kinematic and ground reaction force
513 accommodation during weighted walking. *Human Movement Science*. 2015 Dec 1;44:327–
514 37.
- 515 43. Minetti AE, Alexander RMcN. A Theory of Metabolic Costs for Bipedal Gaits. *Journal of*
516 *Theoretical Biology*. 1997 Jun 21;186(4):467–76.

- 517 44. Bode VG, Frykman PN, Smith NI, Fellin RE, Seay JF. Spatiotemporal and Kinematic
518 Comparisons Between Anthropometrically Paired Male and Female Soldiers While Walking
519 With Heavy Loads. *Military Medicine*. 2021 Feb 26;186(3–4):387–92.
- 520 45. Fumery G, Fourcassié V, Moretto P, Bourg V. Analysis of gait during independent and
521 paired walking in adults with an intellectual disability: A case report. *J Rehabil Med-CC*.
522 2018;1(1):1000009.
- 523 46. Sghaier N, Bellhari-Trahin S, Marin F, Ben Mansour K. How to estimate the transparency
524 assistance of a passive exoskeleton ? a Case Study. *Comput Methods Biomech Biomed Eng*.
525 3 oct 2019;22(sup1):S460—S462.
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