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# 1 **The impact of collective load transport on the individual walking**

2 N. Sghaier<sup>1</sup>, C. Pasquaretta<sup>1</sup>, N A. Turpin<sup>2</sup> & P. Moretto<sup>1\*</sup>

3 <sup>1</sup> CRCA, Université Paul Sabatier, Toulouse, France.

4 <sup>2</sup> IRISSE, Université La Réunion, La Réunion, France.

5 \* Email: [Pierre.moretto@univ-tlse3.fr](mailto:Pierre.moretto@univ-tlse3.fr)

## 6 **1. Abstract**

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

## 17 **2. Introduction**

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

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

32 So far, mainly individual liftings have been studied (Datta & Ramanathan, 1971; Heglund  
33 et al., 1995). According to these researches, the best way to carry a load individually in terms  
34 of ergonomics is to use the double pack mode and the head mode. In contrast, carrying the load  
35 by hand was the worst method to transport a load. These data mainly suggested that the load  
36 should be as aligned as possible with the center of mass of the subjects to avoid creating a  
37 destabilizing torque. However, the ergonomic evaluations were only based on physiological  
38 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 activities (Gamble et al., 1991) or military (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 recovery

45 (Knapik, Harper & Crowell, 1999; Leyk et al., 2006, 2007). Armstrong et al. (2020), ranked  
46 paramedic lifting task using a measure of biomechanical exposure and showed that the worst  
47 activity while working was lifting a scoop board from the ground to the waist. Moreover, they  
48 showed that the position of the carrier, head or foot end of the equipment, didn't modify the  
49 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 load  
52 transport and considered it as a quadrupedal gait. The results showed an overall modification  
53 in gait parameters such as step length, gait cycle time and, Center of Mass vertical displacement  
54 associated to a walking gait synchronization of the participant. Sensory and tactile feedback in  
55 human walking helps dyads to synchronize their movements during side-by-side walking  
56 (Nessler & Gilliland, 2009; Zivotofsky, Gruendlinger & Hausdorff, 2012; Sylos-Labini et al.,  
57 2018; Felsberg & Rhea, 2021). Fumery et al. (2018), studied the walking efficiency during a  
58 side-by-side collective load transport and, showed the ability of humans to collaborate  
59 efficiently during load carriage. However, all of these researches focused more on the collective  
60 modifications during a load transport and not on how the collective tasks impacted the  
61 individual performance. This collective movement could be mainly performed in two ways: (1)  
62 the team members look at each other and (2) they look at the same direction to transport a load.  
63 The second technique implies a forward and a backward walking of one team member, which  
64 could play a major role in the individual and collective performance of the load transport. For  
65 now, most of the researches described the backward walking pattern as a simple kinematic time  
66 reversal of the forward walking pattern and reported only few differences (Thorstensson, 1986;  
67 Winter, Pluck & Yang, 1989; Lee et al., 2013). However, backward walking in a collective  
68 transport task has not been investigated.

69 In this research we looked forward to explore different aspects of a collective stretcher, and  
70 mainly how does this kind of transport impact the biomechanical individual behavior. The  
71 objective of this research is to address three scientific questions: (1) What are the differences  
72 across forward and backward walking? (2) How a collective load transport impacts the  
73 biomechanics of an individual forward walking? and, (3) Does the backward walking play a  
74 major role in the biomechanical modification during collective load transport?

### 75 **3. Materiels and methods**

#### 76 **1.1. Population**

77 Twelve women and eight men were recruited from September 01, 2019, to July 01, 2022.  
78 All participants were free of musculoskeletal or neurological disorder that might have affected  
79 the carriage. Mean ( $\pm$ s.d.) age, height and body weight were  $24 \pm 2,6$  years,  $1,71 \pm 0,07$  cm and  
80  $64,65 \pm 8$  kg, respectively. Each duo was matched by gender, height and weight. The project  
81 was approved by the University Review Board and all participants gave their written and, oral  
82 consent in accordance with the Helsinki convention.

#### 83 **1.2. Experimental**

84 In total, 10 dyads performed four different lifting conditions. For the two first conditions,  
85 we instructed the participants to walk individually at their own pace in a Forward direction  
86 “C1” and, in a Backward direction “C2”. Then two collective conditions consisted in  
87 transporting collectively a stretcher shaped load of 1.2 kg with the participant 1 at the front and  
88 the participant 2 at the back (Figure 1.c). We instructed the participants to transport the stretcher  
89 shaped load while looking at the same direction (Figure 1.a); meaning that both participants

90 were performing a forward walking “C3”. And we instructed them to perform the same  
91 condition while looking at each other (Figure 1.b); meaning that the participant 1 was  
92 performing a backward walking and, the participant 2 was performing a forward walking “C4”.  
93 All conditions were randomly presented. Three trials were recorded in each condition.

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

### 97 **1.3. Kinematic data acquisition**

98 Motion capture data were collected using 20 infrareds (11 Vero V2.2, 7 MX3 and, 2 MX  
99 TS40) transmitter-receiver video cameras (Vicon, Oxford metric’s, Oxford, United Kingdom)  
100 sampled at 200 Hz. Forty-two retro-reflective markers were placed on bony landmarks and on  
101 the navel of each participant (Wu *et al.*, 2002, 2005), and 13 on the stretcher shaped load. One  
102 gait cycle per trial and participant has been considered for the analysis. These cycles were  
103 selected close to the middle of the travel path to avoid the acceleration and deceleration phases.  
104 The gait cycle of walking is defined by two successive foot strikes of the same foot. Regarding  
105 the collective transport C3 and C4, we investigated the Poly-Articulated Collective System  
106 (PACS) gait cycle, formed by the two participants and the load they carry, and defined by the  
107 first heel strike of the participant 2 (at the back) and the second foot strike of the participant 1  
108 (at the front). The three-dimensional reconstruction of the markers position was performed  
109 using the Vicon Nexus 2.11.0 software.

## 110 1.4. Computed parameters

### 111 1.4.1. Gait parameters

112 **Step length** was computed as the distance travelled between the foot strike of one foot and  
113 the strike of the contralateral foot.

114 **Gait Cycle Time** was computed as the time between two consecutive foot strikes of the  
115 same foot.

### 116 1.4.2. CoM trajectory

117 De Leva anthropometric table (de Leva., 1996) was used to estimate the masses of each  
118 segment ( $m_i$ ), the position of the center of mass of each segment  $i$  ( $CoM_i$ ) of the participants  
119 and to determine the global position of the CoM of each carriers (i.e.  $CoM_{Participant1}$ ,  
120  $CoM_{Participant2}$ ) and of the whole Poly-Articulated Collective System (PACS) which included  
121 the two subjects and the carried load ( $CoM_{PACS}$ ). The participants and PACS CoM location  
122 were all computed in the global frame of reference  $R(0, x, y, z)$  as follows ( $m_{Participant1/2}$ ,  
123 Participant 1 or 2 mass;  $m_{PACS}$ , PACS mass) :

$$124 \quad \overrightarrow{OCoM}_{Participant1/2} = \frac{1}{m_{Participant1/2}} \sum_{i=1}^{n=16} m_i \overrightarrow{OCoM}_i$$

$$125 \quad \overrightarrow{OCoM}_{PACS} = \frac{1}{m_{PACS}} \sum_{i=1}^{n=33} m_i \overrightarrow{OCoM}_i$$

126 We then assessed the vertical amplitude ( $A = Z_{max} - Z_{min}$ , with  $Z$  the CoM height), the  
127 CoM period ( $P$ , which refers to the time between two peaks of the  $z$ -position curve) and, the  
128 CoM Velocity (Winter (1995)).

129 **1.4.3. 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; Sghaier  
132 *et al.*, 2022). RR is related to the consistency of the locomotor pattern and is based on the  
133 analysis of an inverted pendulum system (IPS) (Cavagna, Saibene & Margaria, 1963; Willems,  
134 Cavagna & Heglund, 1995; Gomeñuka *et al.*, 2014). RRà was computed for each participant  
135 and the PACS as follow:

136 
$$RR = 100 \frac{W_{kf} + W_v - W_{ext}}{W_{kf} + W_v}$$

137 With  $W_{kf}$  the forward kinetic,  $W_v$  the vertical work and  $W_{ext}$  the external work. These  
138 parameters were computed according to the method of Bastien *et al.* (2016).

139 **1.4.4. Joint angles**

140 In order to study the kinematic modifications during a walking and a transporting task, we  
141 computed the joint angles at the hip, knee and ankle joints during a complete gait cycle. These  
142 joint kinematic were calculated according to the method proposed by the “Standardization and  
143 Terminology Committee” of the ISB, which defined a set of coordinate systems for various  
144 joints of the lower body based on the joint coordinate system and the XYZ sequence (Wu &  
145 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 has been reversed from 100% to 0% of the gait cycle to compare  
149 backward to forward walking.

## 150 **1.5. Statistical Analysis**

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

152 We compared the 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 models approach.

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

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

156 In order to analyze joint angle evolution, we used the Laassel *et al.* (1992) method. The gait

157 cycle was divided into 25 windows, each of 4% of the gait time duration. To evaluate the effect

158 of backward walking on the individual and collective walking, we ran 6 different linear models

159 for each participant (P1 and P2) and each joints (hip, knee and ankle). Each model was built

160 using conditions, windows and their interaction as predictors and angles as response variable.

161 We then estimated the angle marginal means and their confidence interval for each condition

162 in each window using the package *emmeans* in R.

## 163 **4. Results**

### 164 **1.6. Gait parameters**

165 The step length of participant 1 and 2 where significantly longer for C1 compared to C2

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

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

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

169 lengths during C2 were significantly shorter than those performed during C1 (-35.3%), C3 (-

170 22.9%) and C4 (-15.1%).

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

175 Globally for the GCT, there were no significant differences for the participant 1 between  
176 the different conditions. However, Participant 2 GCT was 7% greater in the collective  
177 conditions (C3, C4) than in the individual conditions (C1, C2). In addition, the GCT of C4 was  
178 4.3% longer than the one of C3 (Figure 2.d).

### 179 **1.7. Center of Mass (CoM) excursion**

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

187 **Figure 3 : Center of Mass mean vertical excursion ( $10^{-2}$ ) for participant 1 (a) and (b), participant**  
188 **2 (b) and (c) and, PACS (d). Continuous lines represent the individual conditions C1 and C2 and,**  
189 **the dashed lines represent the collective conditions C3 and C4. The black line correspond to the**  
190 **forward walking performance and, the blue ones to the backward walking performance.**

191 **1.8. CoM velocity**

192 For P1 the velocity performed during the first condition of individual walking decreased  
193 significantly for C2, C3 and, C4 (respectively by 21.6%, 10.9% and, 19.3%), which is also the  
194 case for P2 (respectively by 24.6%, 11.9% and, 21%) (Figure 4.a,b). Forward walking appears  
195 always faster than backward walking whether the participants are linked or not. Indeed, P1 and  
196 P2 increased their walking speed by 13.6% and 16.7% from C2 to C3. This is confirmed from  
197 C3 to C4 with a mean decrease of 10% for P1 and P2. Individually, backward walking induces  
198 a 23% decrease of the velocity (Figure 4.c). It is confirmed when the participants carry the load.  
199 The velocity of the PACS during C3 decreased by 9.9% compared to the one computed for C4  
200 (Figure 4.d).

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

205 **1.9. Recovery rate**

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

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

### 218 **1.10. Joint angles (Hip- Knee-Ankle)**

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

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

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

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

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

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

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

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

254 The results of ankle dorsi/plantar flexion reveal an increase of the dorsiflexion during C2  
255 and C4, by 27.1% and 56.5% at 36% of the cycle, respectively. At the initial swing phase, the  
256 plantar flexion reached 12° in C3 and 9° in C1 at 65% of the cycle, while, the ankle joint reached  
257 a plantar flexion limited to approximatively 7° at 92% of the cycle. Besides, the plantar flexion  
258 was 95.3% higher in C4 collective performance than for the C2 individual performance.

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

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

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

## 267 **5. Discussion**

268 The purpose of this study investigate how a collective task such as stretcher transport  
269 influence the individual walking patterns. We used two load transport configurations with  
270 subject looking at the same direction or in the opposite direction while transporting the load,  
271 and compared the walking pattern with individual walking pattern without load. We studied the  
272 differences across forward and backward walking, compared individual walking to linked  
273 walking and, studied the impact of a backward walking on a linked walking. The results showed  
274 that the collective task modifies the spontaneous walking pattern but only/mainly for one  
275 participant.

276 We first compared the spatiotemporal parameters when performing a forward walking and  
277 a backward walking. Accordingly to Fritz et al., (2013) and Lee et al., (2013), a reduction of  
278 the step length and the CoM velocity during condition 2 were observed. The walking velocity  
279 is depending on the step length (JudgeRoy, Davis & Ounpuu, 1996). Unlike forward walking  
280 “C1”, backward walking “C2” is occasionally used in the human range of motion despite it

281 alters the movement efficiency. In addition, we instructed the participants to look straight ahead  
282 during C2 meaning there was an absence of a visual feedback. Studies explained that in order  
283 to reduce their subjective instability, participants had to reduce their step length so as their speed  
284 (Grasso, Bianchi & Lacquaniti, 1998). Besides, the diminution of the average range of the hip  
285 flexion/extension induced the diminution of step length parameters (Perry, K & Davids, 1992).  
286 These results, though, did not impact the gait cycle time, which was globally around 1 second  
287 for both conditions.

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

298 The vertical Center of Mass (CoM) excursion has been widely for normal and pathological  
299 walking. However, very few described the ones occurring during a backward walking and, even  
300 less for collective transport. Our main result showed, a diminution of CoM amplitude across  
301 individual walking, forward and backward, which can be explained by the velocity decrease  
302 and the limitation of movement. This limitation occurs mainly at the terminal stance (50% of  
303 the gait cycle). In fact, for a forward walking the hip extension reaches the 10°, whereas, for a  
304 backward walking the hip extension is not present.

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

326 Concerning the collective transport, we recorded two conditions where the main difference  
327 was the position of the participant 1. In the C3 collective condition, both participants looked at  
328 the same direction. The results obtained showed that both participants reduced their speed when  
329 transporting the load. Multiple research showed that during individual walking, when the load

330 weight tends to increase, the spontaneous velocity tends to decrease, due to the step length  
331 reduction (James et al., 2015). These modifications allow humans to spontaneously adopt an  
332 optimal gait and walking speed to minimize the energetic cost (Minetti & Alexander, 1997;  
333 Bode et al., 2021). Yet, in our study, we choose a negligible weight of the transported object,  
334 to focus on the effect of a physical link across the participants. This means that the observed  
335 modifications were only due to their link that induced the first step of a collaborative task.

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

346 For P1, the collective load transport did not impact his RR performance, and no difference  
347 was found across individuals and collective performance for forward and backward walking.  
348 Whereas, P2 constantly modified his behavior depending on the condition. P2 RR decreased  
349 when he performed “C3” and even more when he performed “C4”. Fumery et al.(2018b),  
350 studied paired walking of adults with intellectual disabilities and showed that when the  
351 participant is paired to a healthy individual, there is an improvement of spatiotemporal of the  
352 disabled participant and a decrease of the healthy participant pattern. In our study it seems that  
353 P2, plays an important role in the constant kinematic readjustment given that he has more  
354 environment inputs and that the backward walking disturbed P1 efficiency.

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

360        The objective of the condition “C4” was to see if the backward walking performed by the  
361 participant 2 impacted the kinematic individual performance of the participant 1 as well as the  
362 collective performance. Kinematic results of participant 1 showed higher flexion values for  
363 each of the hip, knee and, ankle when comparing the individual backward performance “C2”.  
364 On the contrary, no kinematic modifications were found for the participant 2.

365        Regarding the diad performance, we focused on the Poly-Articulated Collective System  
366 (PACS) formed by the two participants and the load they transported. As done for the  
367 participants, we computed the PACS velocity and Recovery Rate, with the purpose to bring out  
368 how P1 placement impacted the collective performance. Both collective conditions replicate  
369 two types of collective stretcher transport. Our results showed a velocity decrease of the PACS  
370 from “C3” to “C4”. Which can be explained by the velocity individual decrease of each  
371 participant. The Recovery Rate also decreased by 10% from “C3” to “C4”. These two results  
372 join those found by Sghaier et al. (2022), who studied a collective side-by-side load transport  
373 associated to a precision constraint and, showed a decrease of the PACS velocity and Recovery  
374 Rate. The amplitude of the CoM displacement also showed a decrease from “C3” to “C4”.  
375 These results illustrate a better collective efficiency for “C3”, meaning when the two  
376 participants performed both a forward walking and looked at the same direction. This also  
377 means that the backward walking during the collective transport affects the efficiency of the  
378 collective work.

## 379 **6. Conclusion**

380 The present study give insight on how a collective load transport modify the individual  
381 walking performance. We first compared individual forward and backward walking. As stated  
382 by the literature we observed a kinematic time reversal of the flexion/extension angles.  
383 However, we observed major modifications in the flexion/extension amplitude and a delay of  
384 the occurrence of some crucial time points inducing a modification of some spatiotemporal  
385 parameters. Then we studied the impact of a collective load transport on the individual walking  
386 performance. When the participant looked at the same direction, we observed a slight kinematic  
387 modification of the participants. Yet, the linked task induced a decrease of spatiotemporal  
388 parameters. However, when the participants looked at each other during the carriage, we  
389 observed higher flexion values for participant 1, added to the decrease of spatiotemporal  
390 parameters. The efficiency of the collaborative task decreased when the participant looked at  
391 each other as shown the decrease of the recovery rate. This result indicates that the major  
392 component impacting the efficiency of a collective load transport was the performance of a  
393 backward walking by the participant 1. Moreover, the efficiency of the collaborative task was  
394 mainly controlled by the participant 2 with more environment information. He adjusted  
395 systematically his behavior (spatiotemporal parameter) in order to adapt to the other participant  
396 who was performing a backward walking. Future research should study the forces interaction  
397 across participants in order to understand the involvement of each participant.

## 398 **7. Acknowledgments**

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400 18-CE10-0003].

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# 1 The impact of collective load transport on the individual walking

2 N. Sghaier<sup>1</sup>, C. Pasquaretta<sup>1</sup>, N A. Turpin<sup>2</sup> & P. Moretto<sup>1\*</sup>

3 <sup>1</sup> CRCA, Université Paul Sabatier, Toulouse, France.

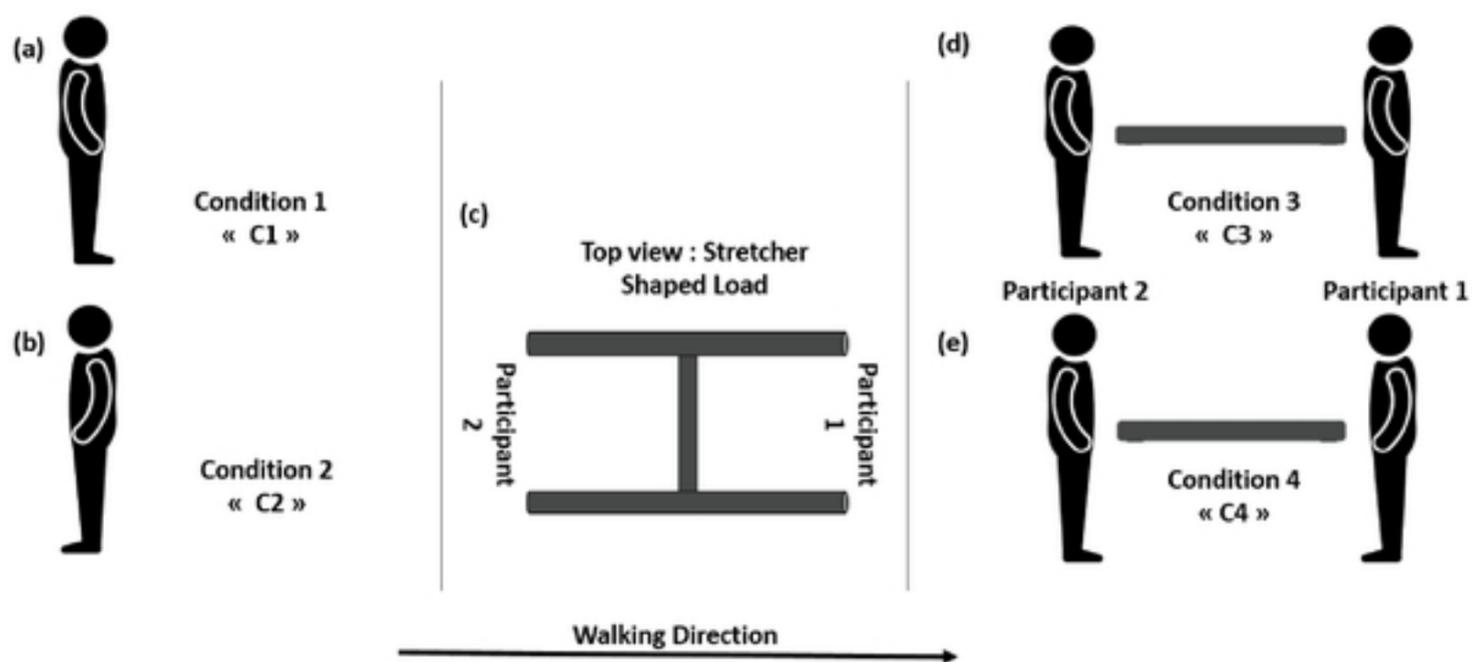
4 <sup>2</sup> IRISSE, Université La Réunion, La Réunion, France.

5 \* Email: [Pierre.moretto@univ-tlse3.fr](mailto:Pierre.moretto@univ-tlse3.fr)

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

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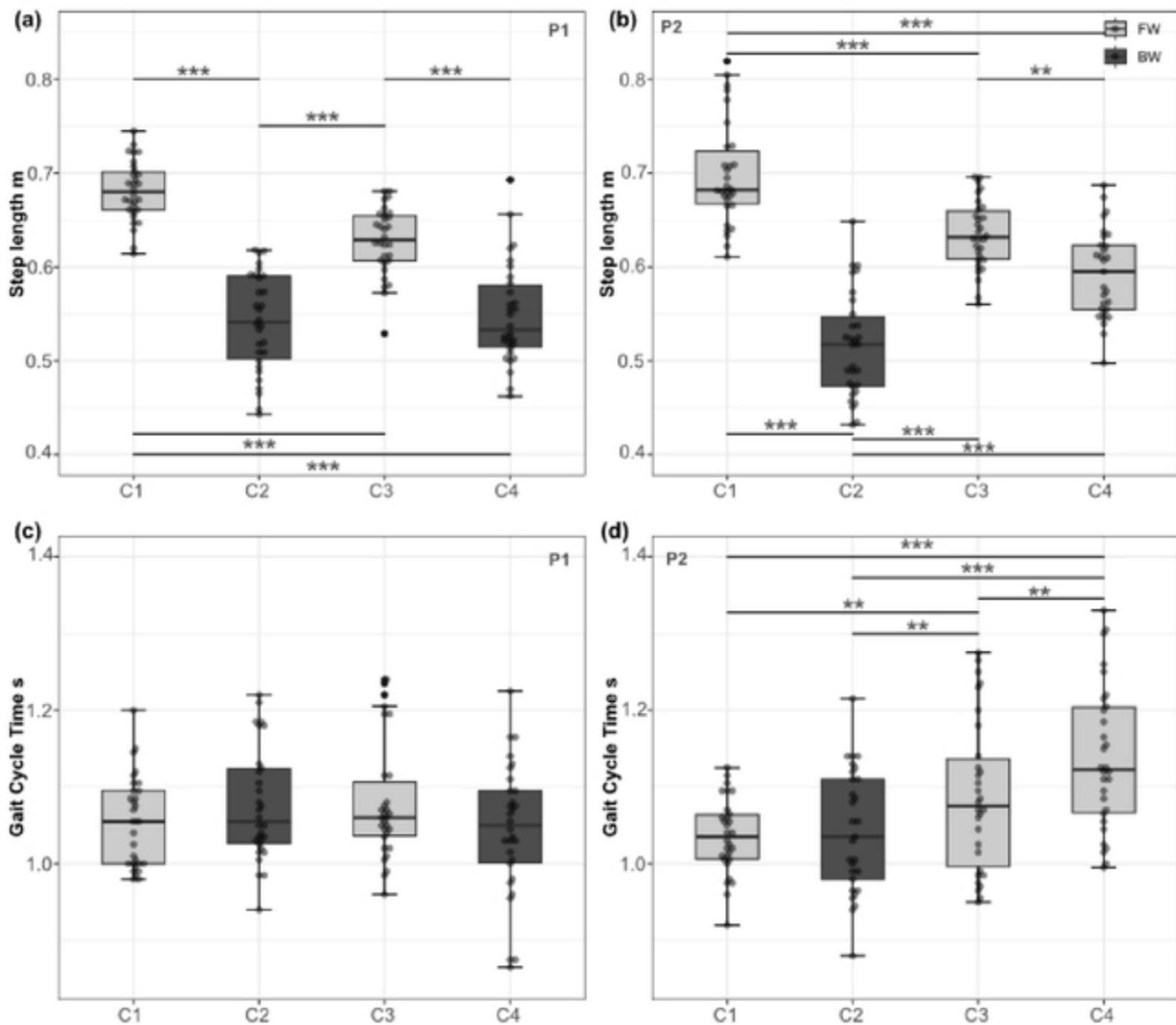
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8 **Figure 1: Step length and Gait Cycle time boxplot for participant 1 respectively (a), (c) and**  
9 **participant 2 (b) and (d) for condition 1,2, 3 and, 4. Light grey boxplots represent the forward**  
10 **walking performance and, dark grey boxplots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

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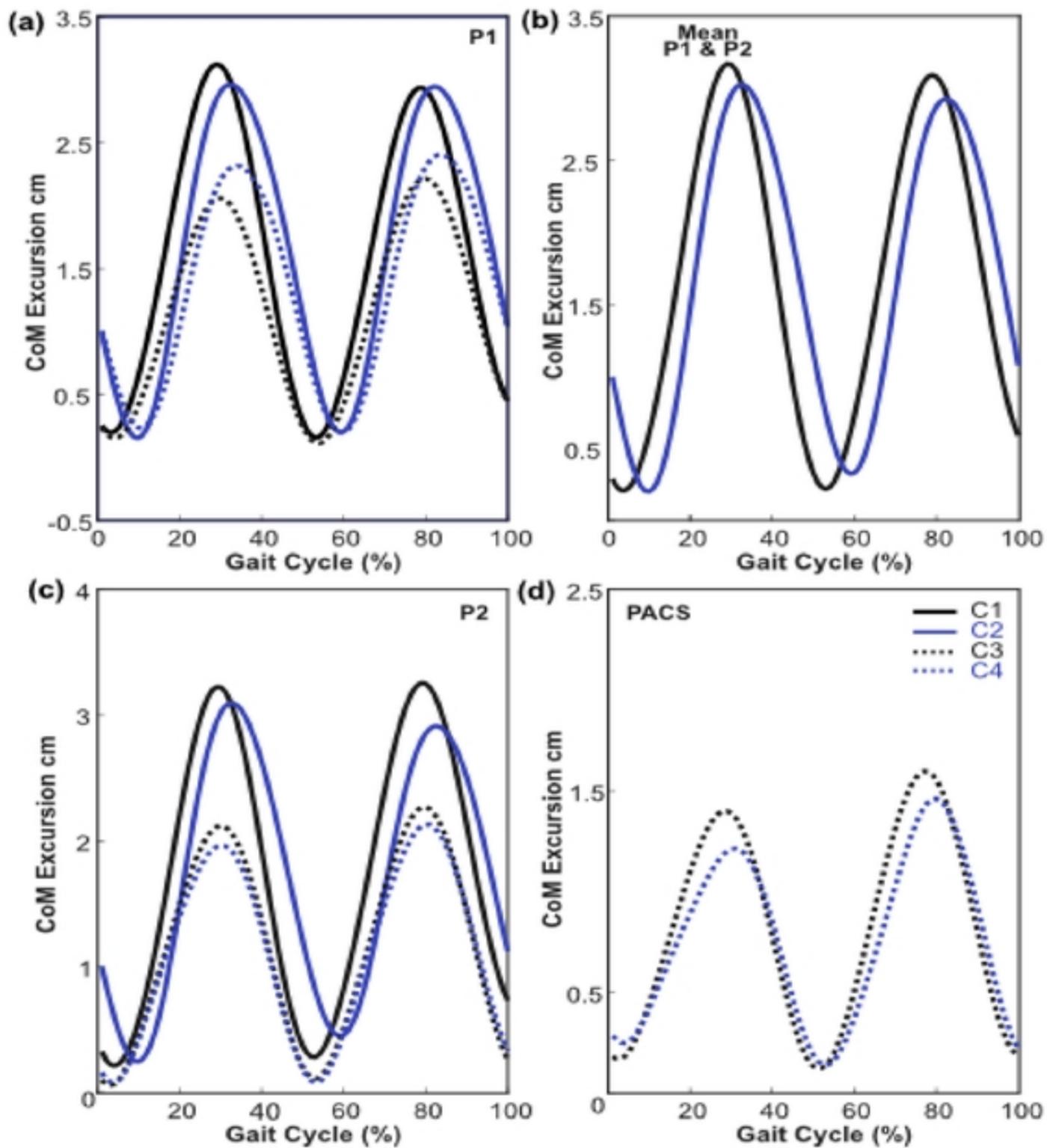
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8 **Figure 1 : Center of Mass mean vertical excursion ( $10^{-2}$ ) for participant 1 (a) and (b), participant**  
9 **2 (b) and (c) and, PACS (d). Continuous lines represent the individual conditions C1 and C2 and,**  
10 **the dashed lines represent the collective conditions C3 and C4. The black line correspond to the**  
11 **forward walking performance and, the blue ones to the backward walking performance.**

1 **The impact of collective load transport on the individual walking**

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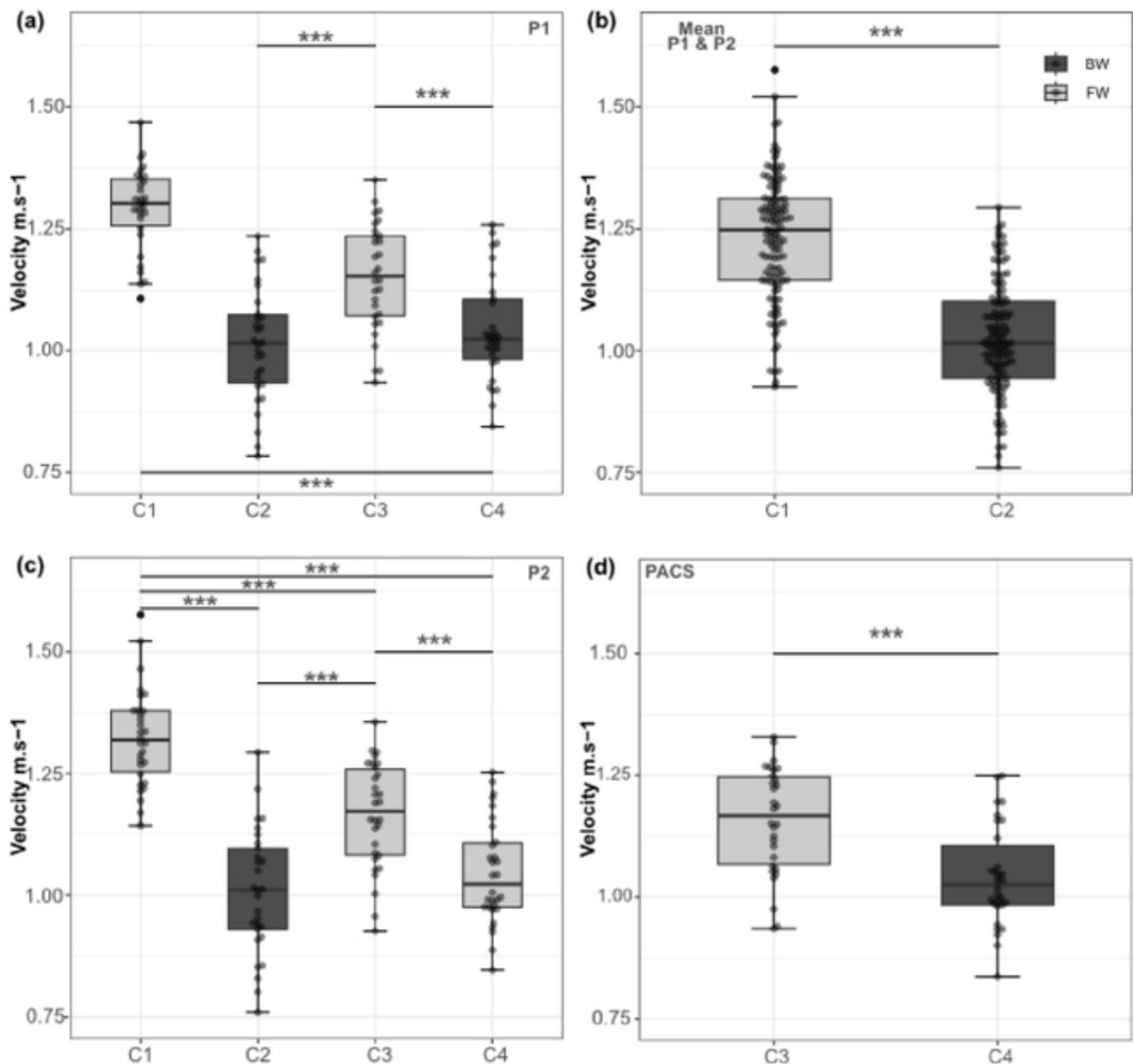
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9 **Figure 1 : Center of Mass velocity (m.s<sup>-1</sup>) boxplots for participant 1 (a) and (b), participant 2 (c)**  
10 **and (b) and, PACS (d). for condition 1,2, 3 and, 4. Light grey boxplots represent the forward**  
11 **walking performance and, dark grey boxplots represent the backward walking performance(\***  
12 **p< 0,05; \*\* p<0,01 and; \*\*\* p<0,001).**

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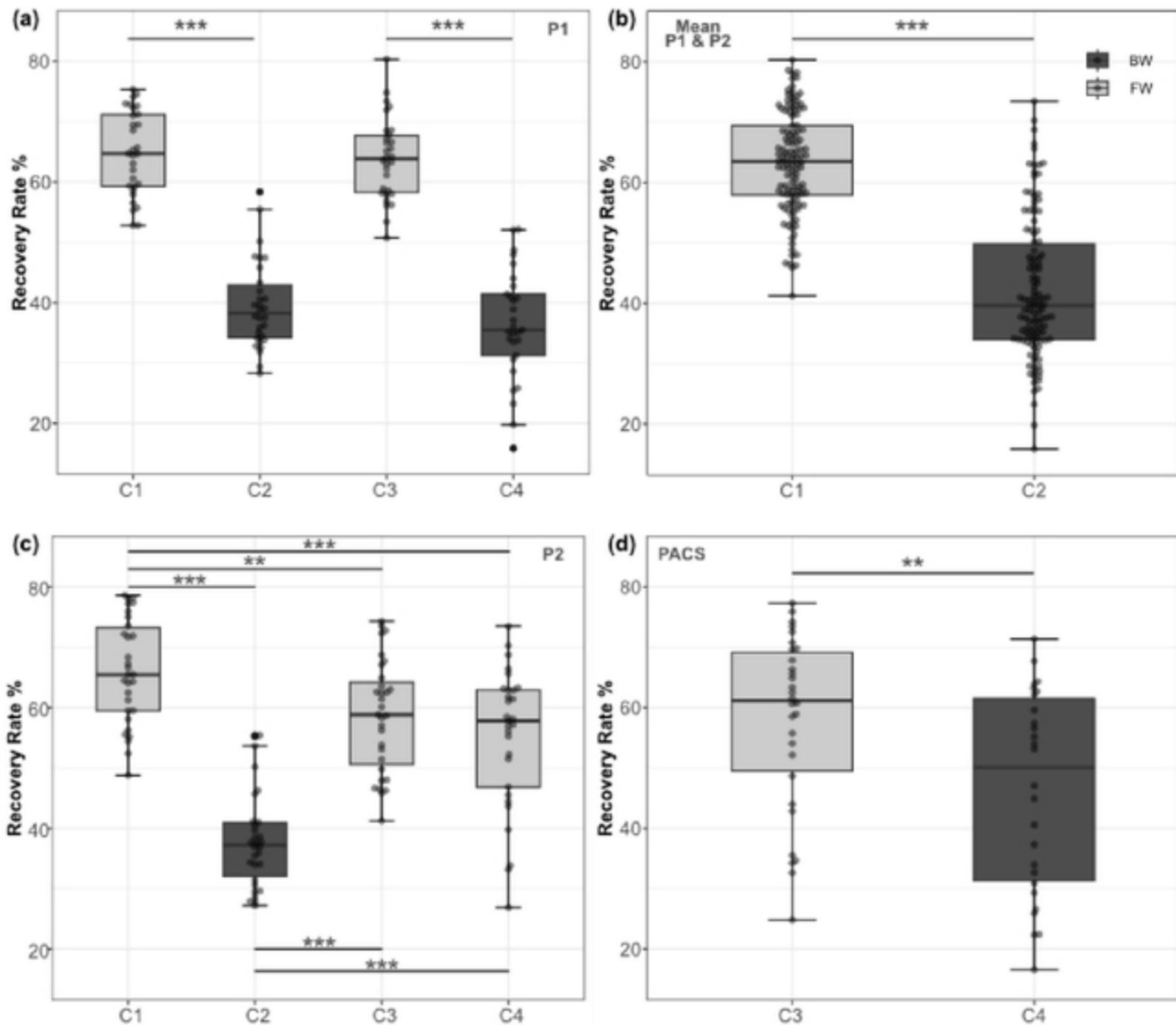
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10 **Figure 1 :Recovery Rate (%) boxplots for participant 1 (a) and (b), participant 2 (c) and (b) and,**  
11 **PACS (d). for condition 1,2, 3 and, 4. Light grey boxplots represent the forward walking**  
12 **performance and, dark grey boxplots represent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

1 **The impact of collective load transport on the individual walking**

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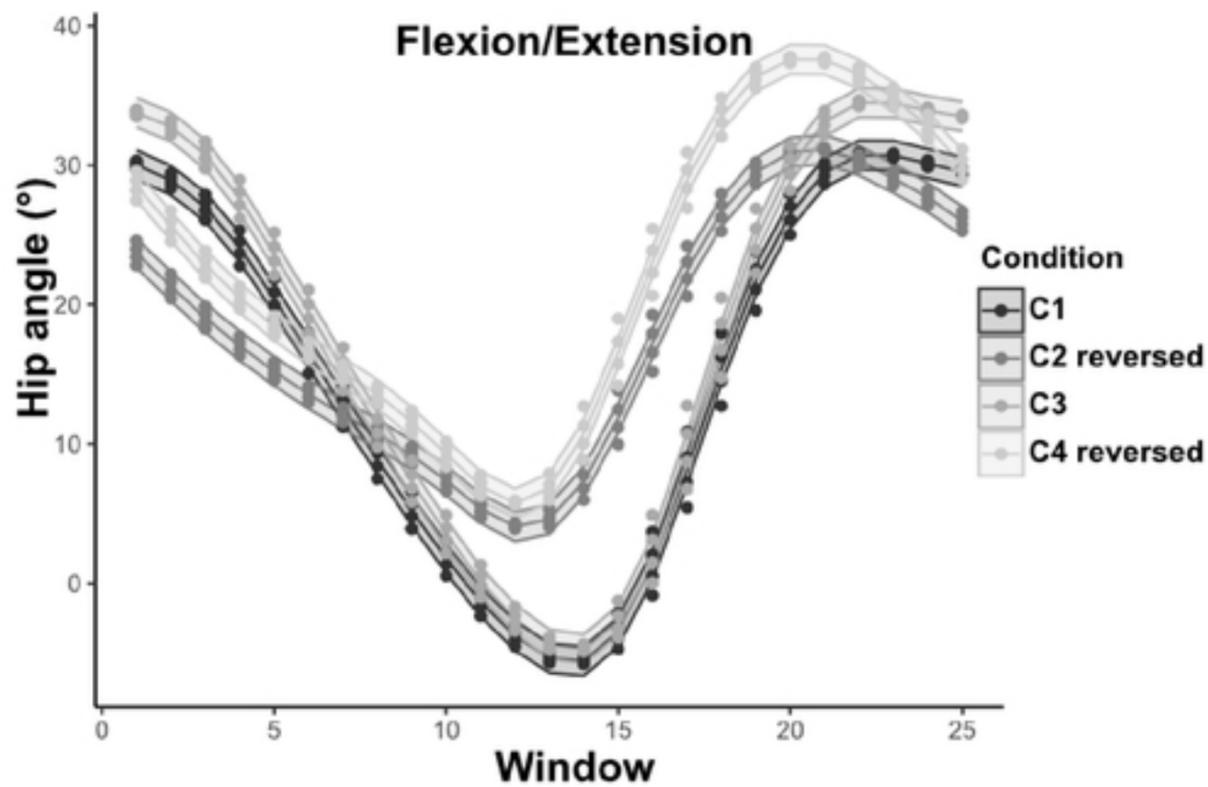
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11 **Figure 1 : Participant 1 hip flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**  
12 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 and C3 curves are**  
13 **reversed in time.**

1 **The impact of collective load transport on the individual walking**

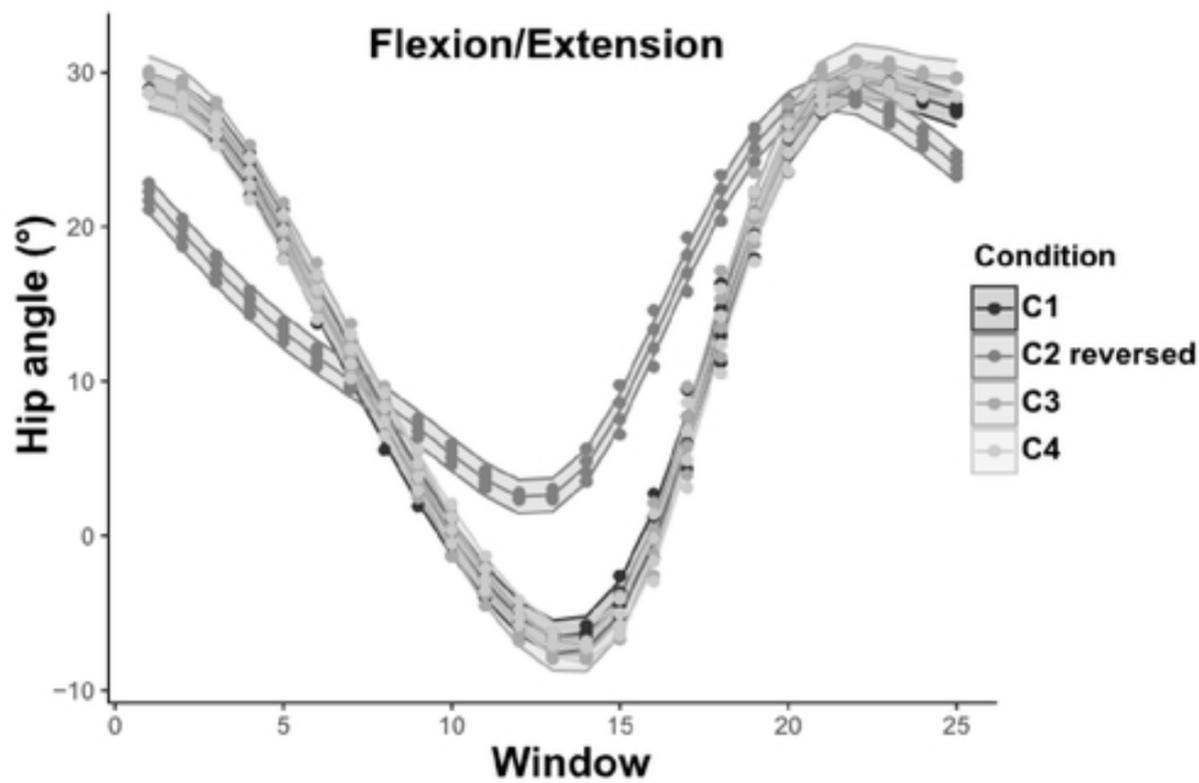
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5 \* Email: [Pierre.moretto@univ-tlse3.fr](mailto:Pierre.moretto@univ-tlse3.fr)

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

1 **The impact of collective load transport on the individual walking**

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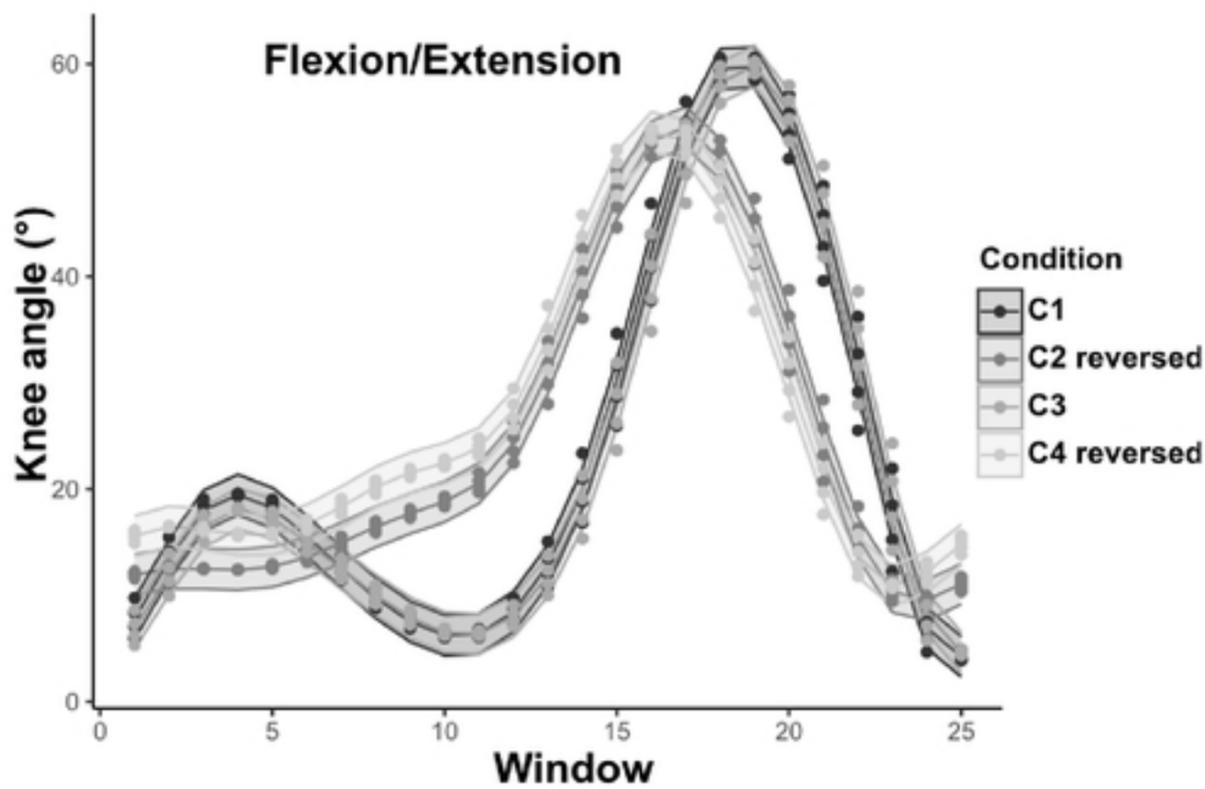
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10 **Figure 1 : Participant 1 knee flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**  
11 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 and C3 curves are**  
12 **reversed in time.**

# 1 The impact of collective load transport on the individual walking

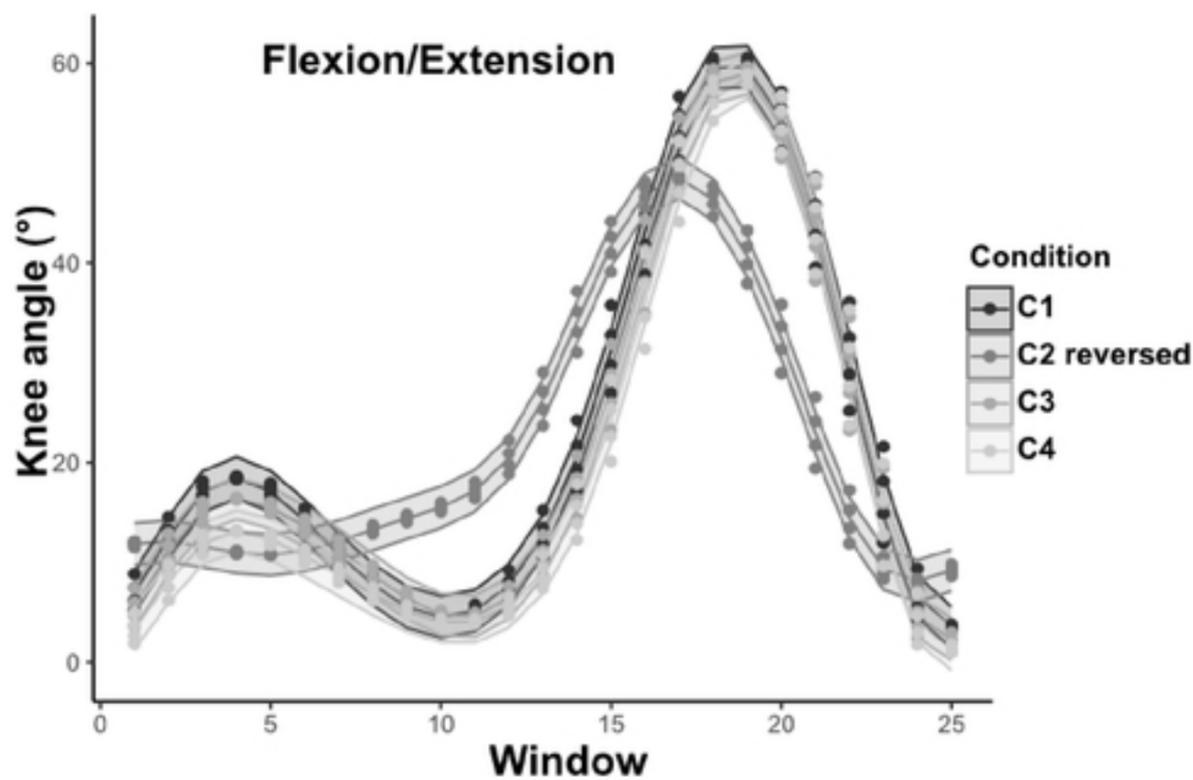
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8 **Figure 1 : Participant 2 knee flexion/extension (°) for the condition 1, 2, 3 and, 4. The curves**  
9 **correspond to the 95 confidence interval of each 4% of the gait cycle. The C2 curve is reversed**  
10 **in time.**

# 1 The impact of collective load transport on the individual walking

2 N. Sghaier<sup>1</sup>, C. Pasquaretta<sup>1</sup>, N A. Turpin<sup>2</sup> & P. Moretto<sup>1\*</sup>

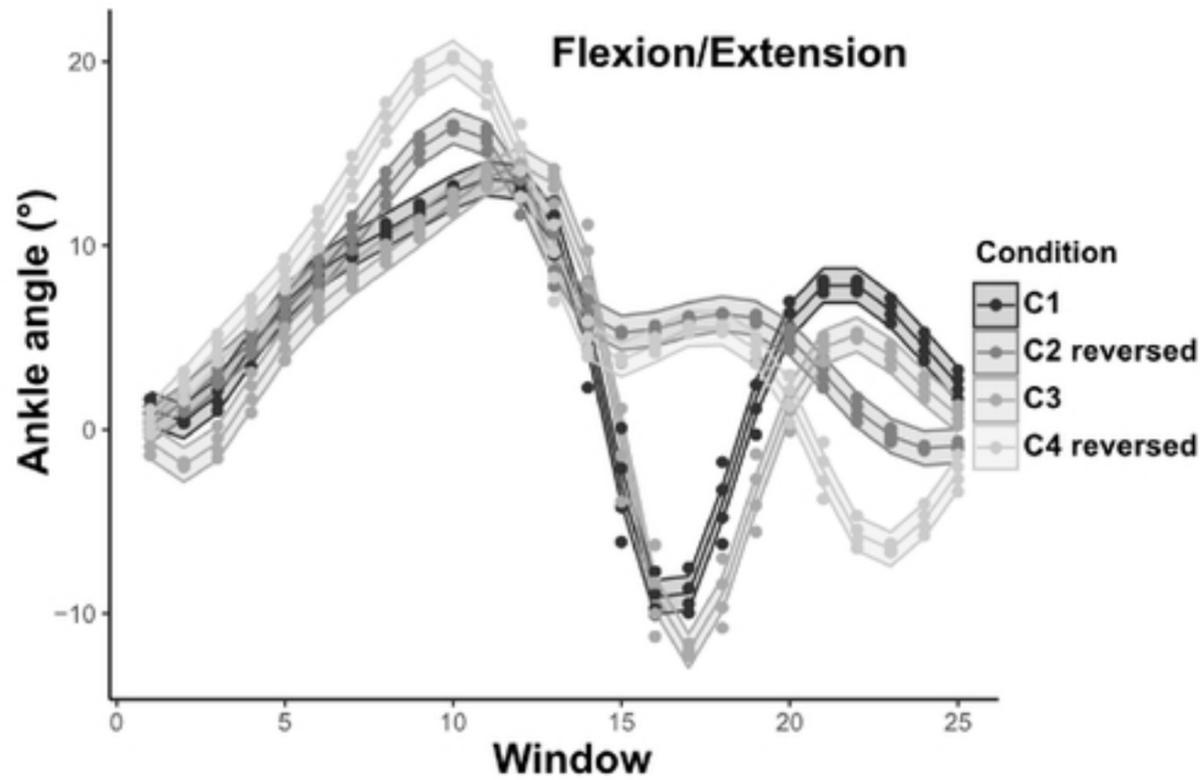
3 <sup>1</sup> CRCA, Université Paul Sabatier, Toulouse, France.

4 <sup>2</sup> IRISSE, Université La Réunion, La Réunion, France.

5 \* Email: [Pierre.moretto@univ-tlse3.fr](mailto:Pierre.moretto@univ-tlse3.fr)

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8

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

1 **The impact of collective load transport on the individual walking**

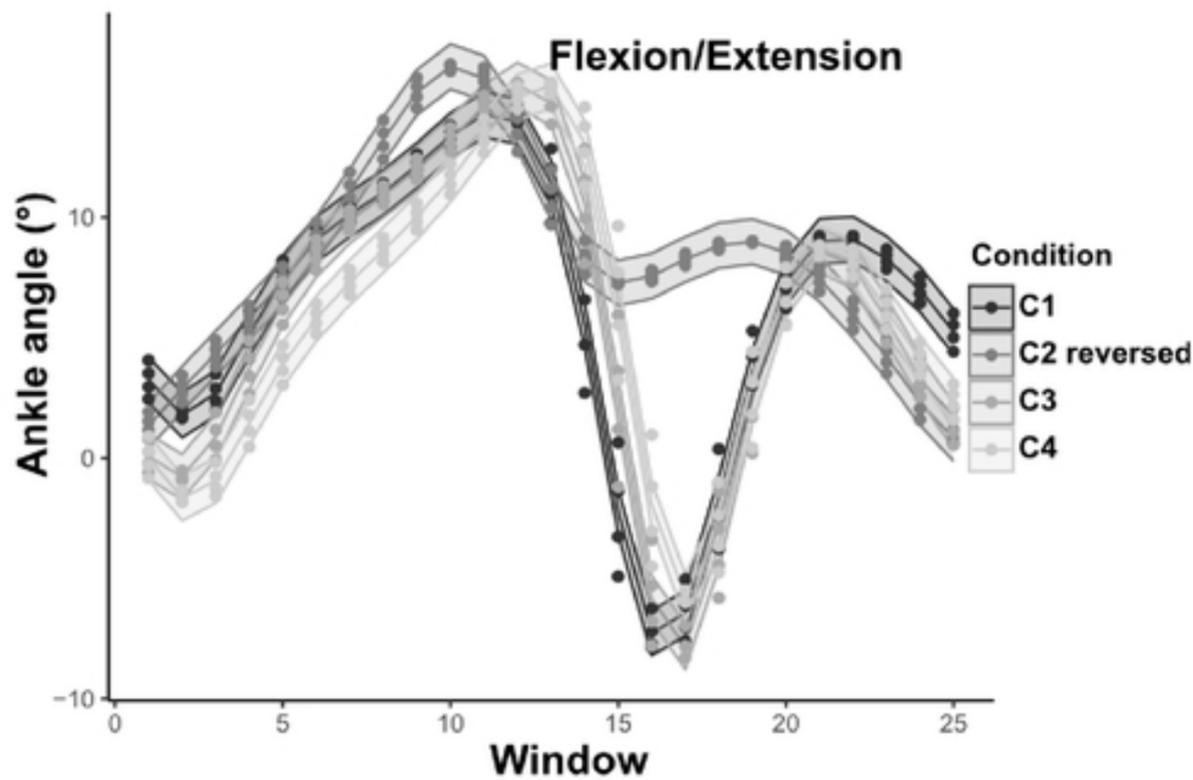
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7

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