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## Locomotor pattern and mechanical exchanges during collective load transport

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26 have to move heavy loads together or in clinical environments when caretakers have  
27 to move a patient. Therefore, a better understanding of the biomechanics of  
28 collective load carriage could have potential applications in the field of ergonomics.  
29 Finally, collective load carriage is one of the exercises regularly performed by  
30 athletes in sports. For example, the CrossFit program (i.e. CrossFit daily training or  
31 CrossFit events, Feito et al., 2018) needs to move loads by team regularly.

32 Cavagna et al. (1963, 1977) were the first to propose the inverted pendulum  
33 system (IPS) model to explain the economy of gait in humans. In this model the  
34 oscillations of the center of mass of the body (CoM) during stable walking in the  
35 sagittal plane is represented as a wave with constant amplitude and period (Cavagna  
36 et al., 1977; Kuo, 2007). For an ideal pendulum this undulation can be represented by  
37 a sine wave as a function of time. It has been shown that the displacement of the  
38 CoM in humans is not an ideal sine function but is very close to it (Saunders et al.,  
39 1953; Ackerman et al., 2014). The oscillations of the CoM allow the transfer of  
40 potential energy into kinetic energy and *vice versa* on each gait cycle, explaining the  
41 major part of the mechanical economy of walking (Cavagna et al., 2000; Lee and  
42 Farley, 1998). Although there are also during walking some oscillations of the CoM  
43 in the frontal plane due to the movement of the pelvis (Blickhan et al., 2007; Kuo,  
44 1999; Mahaudens et al., 2008) and the stabilization of lateral motion (Kuo, 1999),  
45 they actually contribute for a very weak part of the overall changes in mechanical  
46 energy (Cavagna et al. 1963; Tesio and Detrembleur, 1998). The question we ask in  
47 this paper is whether individuals are able to walk as economically when they are  
48 transporting collectively an object as when they are walking alone and unloaded.

49 Representing the body by its CoM allows to understand a good part of the  
50 biomechanics of locomotion. However, it neglects some important information,

51 namely the variations of kinetic energies at the level of each body segment. Yet, the  
52 study of the mechanical exchanges due to the body segments during collective  
53 carriage could complement the global analysis of the CoM and highlight the  
54 regulation of walking economy. High resolution 3D tracking and reconstruction  
55 techniques (Tesio and Detrembleur, 1998) allow to take this into account by using a  
56 Poly-Articulated Model (PAM) (Moretto et al., 2016; Zatsiorsky and Seluyanov,  
57 1983), i.e. a poly-articulated system of multiple rigid segments, where each segment  
58  $i$  is characterized by a center of mass  $CoM_i$  and a mass  $m_i$ . In this paper, we used this  
59 method to test the general hypothesis that when two individuals are transporting an  
60 object collectively their locomotor pattern (i.e. amplitude and pendulum-like  
61 behavior of the CoM displacement) and their mechanical exchanges (i.e. percentage  
62 of energy recovered, internal, external and total works), are similar to that of an  
63 unloaded individual walking alone.

64

## 65 **2. Materials & methods**

### 66 ***2.1. Participants***

67 Ten pairs of healthy male volunteers, whose characteristics are presented in  
68 Table 1, took part in the experiment.

69 \*\*\*\*\*Table 1 near here\*\*\*\*\*

70 The volunteers had no orthopedic disabilities, no dysfunctions of the  
71 locomotor system, no neurological or vestibular diseases, no visual deficits and no  
72 proprioceptive disorders or dementia. Informed consent was obtained from all  
73 participants. The research was non-invasive and respected a level of activity  
74 practiced daily by the individuals, in accordance with the definition of a non-  
75 interventional study given by the CNRS bioethical office.

76 **2.2. Procedures**

77 The volunteers were tested successively in two experimental conditions: one  
78 in which they walked by pairs but separately (condition Walking Separately: WS)  
79 and the other in which they walked with a box they carry together by two lateral  
80 handles (condition Collective Transport: CT). The mass of the box was 13.41 kg and  
81 its size was 0.40x0.40x0.28 m (Length x Width x Height). A single trial was  
82 performed in the WS condition and three trials in the CT condition (i.e. CT1, CT2,  
83 CT3). During each trial, the volunteers had to walk at spontaneous speed along a  
84 13m-long walkway.

85 **2.3. Data acquisition**

86 Thirteen optoelectronic (11 MX3 and 2 TS40) video cameras (Vicon©,  
87 Oxford) were used to acquire the kinematic data. Forty-two markers were placed on  
88 bony landmarks and on the navel of each volunteer, according to Wu et al. (2002,  
89 2005). Following Ackerman et al. (2014), in order to compare the locomotor pattern  
90 of individuals walking loaded and unloaded, we analyzed the kinematic data of the  
91 two individuals and the load separately, i.e. we considered three separate systems.  
92 The calibrated volume (30 m<sup>3</sup>) was set in the middle of the walkway in order to  
93 record the walking patterns at a stable state walking (i.e. to exclude the acceleration  
94 and deceleration phases at the beginning and at the end of each trial). To allow the  
95 kinematic analysis, the volunteers and the box were reconstructed with the software  
96 Nexus© 1.8.5 (Fig. 1).

97 \*\*\*\*Figure 1 near here\*\*\*\*

98 **2.4. Computed parameters**

99 **2.4.1. Inverted Pendulum System and external work**

100 The Inverted Pendulum System (IPS) model allows us to evaluate the  
101 pendulum-like behavior of the CoM of each volunteer in the WS and CT conditions.  
102 The De Leva's anthropometric tables (1996) allowed us to estimate the mass, the  
103 center of mass position  $CoM_i$  and the radius of gyration of each segment. The global  
104 CoM of each volunteer was then computed from the  $CoM_i$  of their segments.

105 *Sine wave:* To record at least one gait cycle for each individual, a walking  
106 cycle was defined as the interval between two heel strikes of the same leg. One gait  
107 cycle thus consisted of two steps. Following Ackerman et al. (2014), we modeled the  
108 vertical motion of the CoM along time in the sagittal plane as a sine function.

109 The amplitude ( $A = \frac{Z_{max}-Z_{min}}{2}$ ; in meter), angular frequency ( $\omega = \frac{2\pi}{T}$  in  $rad.s^{-1}$ , with  
110  $T$  the period) and phase shift ( $\varphi = \tau * \frac{2\pi}{T}$  in radian, with  $\tau$  the time shift) of the  
111 vertical displacement of the CoM allowed us to determine the function (see Castillo  
112 et al. 2014):

$$113 \qquad Z(t) = A \sin(\omega t + \varphi)$$
$$114 \qquad (1)$$

115 The difference between the vertical displacement of the CoM and the adjusted  
116 sinusoidal function was assessed by the Root Mean Square Error (RMSE). The  
117 RMSE was normalized by the amplitude (RMSE/A), so that we only considered the  
118 error due to the alterations of the periodic signal.

119 *External work:* We computed the kinetic and potential energies, as well as the  
120 external works on the antero-posterior, medio-lateral and vertical axis.

121  $W_{kf}$  is the positive work to accelerate the CoM forwards, calculated as the  
122 sum of the increments of the forward kinetic energy ( $E_{kf}$ , computed on the antero-  
123 posterior axis) along the time curve with:

124 
$$E_{kf} = \frac{1}{2} m \overrightarrow{V}_f^2 (t)_{/R} \quad (2)$$

125

126 where  $m$  is the mass of the individual and  $\overrightarrow{V}_f (t)_{/R}$  is the linear forward velocity of the  
 127 CoM in the Galilean reference frame (R).

128  $W_{kh}$  is the positive work to accelerate the CoM on the medio-lateral and  
 129 antero-posterior axis, calculated as the sum of the increments of the horizontal  
 130 kinetic energy (i.e. the medio-lateral kinetic energy  $E_{kml}$ , computed on the medio-  
 131 lateral axis, plus the forward kinetic energy  $E_{kf}$ ) along the time curve with:

132 
$$E_{kml} = \frac{1}{2} m \overrightarrow{V}_{ml}^2 (t)_{/R} \quad (3)$$

133

134 where  $\overrightarrow{V}_{ml} (t)_{/R}$  is the linear medio-lateral velocity of the CoM in the Galilean  
 135 reference frame (R).

136  $W_v$  is the positive work to move the CoM against gravity, calculated as the  
 137 sum of the increments of the vertical kinetic energy ( $E_{kv}$ , computed on the vertical  
 138 axis) plus the potential energy ( $E_{pot}$ , computed on the vertical axis) along the time  
 139 curve with:

140 
$$E_{kv} = \frac{1}{2} m \overrightarrow{V}_v^2 (t)_{/R} \quad (4)$$

141 and

142 
$$E_{pot} = mgh_{/R} \quad (5)$$

143 where  $\overrightarrow{V}_v (t)_{/R}$  is the linear vertical velocity of the CoM in R,  $g=9.81 \text{ m.s}^{-2}$  the module  
 144 of the acceleration vector due to gravity and  $h_{/R}$  the vertical height of the CoM  
 145 position in R.

146  $W_{ext(sagittal)}$  and  $W_{ext(3D)}$  are the positive external work to raise and accelerate  
 147 the CoM in the sagittal plane and in the three directions of the space (i.e.

148 mediolateral, anteroposterior and vertical axis), respectively. They are computed as  
 149 the sum of the increments of the external mechanical energy ( $E_{\text{ext(sagittal)}}$  and  $E_{\text{ext(3D)}}$ )  
 150 along the time curve (Bastien et al., 2016; Burdett et al., 1983) with:

$$151 \quad E_{\text{ext(sagittal)}} = E_{\text{pot}} + E_{\text{kv}} + E_{\text{kf}}$$

152 (6)

$$153 \quad E_{\text{ext(3D)}} = E_{\text{ext(sagittal)}} + E_{\text{kml}}$$

154 (7)

155 We also computed the energy recovered through the pendulum-like  
 156 oscillations of the CoM ( $RR$ , called recovery rate in Fumery et al., 2018). This metric  
 157 has been proposed by Cavagna et al. (1976) as an indicator of the amount of energy  
 158 transferred between the potential and the kinetic energy of the CoM due to its  
 159 pendulum-like behavior: the closer the value of  $RR$  to 100%, the more consistent the  
 160 locomotor pattern is with the IPS model (Bastien et al., 2016; Cavagna et al., 1963;  
 161 Fumery et al., 2018; Gomenuka et al., 2014; Willems et al., 1995).

162 For the sake of comparison with the data of the literature, we first computed a value  
 163 of the energy recovered for the sagittal plane only ( $RR_s$ , Eq. 8) and then, since we  
 164 had the positions of the markers in 3D, for the three dimensions of the space ( $RR_{3D}$ ,  
 165 Eq. 9).

$$166 \quad RR_s = 100 \frac{W_{\text{kf}} + W_{\text{v}} - W_{\text{ext(sagittal)}}}{W_{\text{kf}} + W_{\text{v}}}$$

167 (8)

$$168 \quad RR_{3D} = 100 \frac{W_{\text{kh}} + W_{\text{v}} - W_{\text{ext(3D)}}}{W_{\text{kh}} + W_{\text{v}}}$$

169 (9)

170 Here, we assumed that the friction forces at the joints and at the ground contacts can  
 171 be neglected. In this condition, the system is submitted only to conservative forces  
 172 and thus the variation of the external mechanical energy is null and the system is



173 conservative. In this case, the system could have a 100% recovery and all potential  
 174 energy would be converted into kinetic energy.

#### 175 2.4.2 Internal work

176 In order to take into account the coordination between all body segments we  
 177 determined the internal work by considering each individual as a poly-articulated  
 178 system consisting of 16 segments.

179 Following the assumption of a conservative PAM, the internal work ( $W_{int}$ ) was  
 180 computed in 3D as the sum of the increments of the  $E_{int,k}$  along the time curve with:

$$181 \quad E_{int,k} = \frac{1}{2} \sum_{i=1}^{16} (m_i \vec{V}_i(t) \cdot \vec{V}_i(t)_{/R^*} + m_i K_i^2 \times \vec{\omega}_i^2_{/R^*})$$

182 (10)

183 where  $m_i$  is the mass of the  $i^{th}$  segment,  $\vec{V}_i(t)_{/R^*}$  the linear velocity of this  $i^{th}$  segment  
 184 CoM in the barycentric reference frame ( $R^*$ , Fig. 1),  $K_i$  the radius of gyration around  
 185 this  $i^{th}$  segment CoM and  $\vec{\omega}_i^2_{/R^*}$  its angular velocity in the  $R^*$  reference frame (Duboy  
 186 et al., 1994).

#### 187 2.4.3 Total work

188 The total mechanical energy of the PAM ( $E_{tot}$ ) was computed as follows in  
 189 3D in the  $R$  reference frame (Leboeuf and Lacouture, 2008; Moretto et al., 2016).

$$190 \quad E_{tot} = E_{pot} + E_{kv} + E_{kf} + E_{kml} + E_{int,k}$$

191 (11)

192 Finally, since the cycle duration was longer in the CT than in the WS condition, in  
 193 order to compare the two conditions we assessed the quantity of energy expended by  
 194 the volunteers and we normalized it per unit of distance. Each work (internal,  
 195 external and total) was thus divided by the distance walked by the volunteers during  
 196 one gait cycle.

#### 197 2.5. Data analysis

198           The data were analyzed with Matlab R2016b© and R 3.4.3©. After checking  
199 for normality, a paired Student *t*-test was used to compare the parameters assessed in  
200 the WS condition and in the first trial of the CT condition. The changes in the three  
201 successive trials in the CT conditions (CT1, CT2 and CT3) were tested with a linear  
202 mixed model (GLMM) with trial number entered as a fixed factor and volunteer  
203 identity as a random variable. The threshold of statistical significance was set at 0.05.

204

### 205 **3. Results**

#### 206 **3.1. Center of Mass trajectory**

207           The CoM velocity (mean±s.d.) was 1.25±0.12 m.s<sup>-1</sup> in the WS condition and  
208 1.28±0.17, 1.36±0.13 and 1.40±0.14 m.s<sup>-1</sup> (CT1, CT2 and CT3 respectively) in the  
209 CT condition. There was no significant difference between WS and CT1 (Student *t*  
210 test: *t*=-1.15, *p*=0.26). However, the CoM velocity was significantly different  
211 between the three trials in the CT condition (GLMM:  $F_{2,40}=29.27$ , *p*<0.01). It  
212 increased by 6.25% between CT1 and CT2 (*t*=5.03, *p*<0.01), by 9.38% between CT1  
213 and CT3 (*t*=7.51, *p*<0.01) and by 2.94% between CT2 and CT3 (*t*=2.47, *p*=0.02).

214 \*\*\*\*Figure 2 near here\*\*\*\*

215           Whether in the WS or CT condition, the vertical displacement of the CoM of  
216 the two individuals was sinusoidal (Fig. 2).

217 \*\*\*\*Figure 3 near here\*\*\*\*

218           The amplitude of the CoM increased by 9.12% between the trial in the WS  
219 condition and the first trial in the CT condition (Fig. 3A, Student *t* test: *t*=2.07,  
220 *p*=0.05). Overall there was a significant increase of the amplitude of the CoM over  
221 the three trials in the CT condition (GLMM:  $F_{2,40}=4.20$ , *p*=0.02). The amplitude  
222 increased by 9.16% between CT1 and CT2 (*t*=2.82, *p*<0.01), but did not differ

223 significantly between CT1 and CT3 ( $t=1.99$ ,  $p=0.05$ ), and CT2 and CT3 ( $t=-0.83$ ,  
224  $p=0.41$ ).

225 The RMSE was not significantly different between the trial in the WS  
226 condition and the first trial in the CT condition (Fig. 3B, Student  $t$  test:  $t=-0.43$ ,  
227  $p=0.67$ ). However, it was significantly different between the three trials in the CT  
228 condition (GLMM:  $F_{2,40}=6.57$ ,  $p<0.01$ ). The RMSE first increased by 63.5%  
229 between CT1 and CT2 ( $t=3.48$ ,  $p<0.01$ ) and then decreased by 29.2% between CT2  
230 and CT3 ( $t=-2.61$ ,  $p=0.01$ ). No significant difference in the RMSE was found  
231 between CT1 and CT3 ( $t=0.87$ ,  $p=0.39$ ).

### 232 **3.2. Inverted Pendulum System**

233 The energy recovered in the sagittal plane (RRs: Fig. 3C) increased from  
234 58.74% in WS to 65.95% in CT1 (Student  $t$  test:  $t=2.44$ ,  $p=0.02$ ). However, there  
235 was no significant difference between the three trials in the CT condition (GLMM:  
236  $F_{2,40}=1.99$ ,  $p=0.15$ ).

237 The energy recovered in 3D ( $RR_{3D}$ : Fig. 3D) also increased and raised from  
238 58.45% in WS to 65.91% in CT1 (Student  $t$  test:  $t=2.50$ ,  $p=0.02$ ). In the same way as  
239 the  $RRs$ , there was no significant difference in the  $RR_{3D}$  between the three trials in the  
240 CT condition (GLMM:  $F_{2,40}=1.83$ ,  $p=0.17$ ).

### 241 **3.3. Total mechanical work**

242 \*\*\*\*Figure 4 near here\*\*\*\*

243 The internal, external and total mechanical work, computed for the two poly-  
244 articulated systems, were not different between WS and CT1 (Fig. 4, Student  $t$  test:  
245  $t=-1.81$ ,  $t=1.09$  and  $t=0.42$  for  $W_{int}$ ,  $W_{ext}$  and  $W_{mecaTot}$ , respectively,  $p>0.05$  in all  
246 cases). Overall, there was also no significant difference between the three trials in the

247 CT condition for  $W_{int}$  (GLMM:  $F_{1,40}=1.07$ ,  $p=0.31$ ),  $W_{ext}$  (GLMM:  $F_{1,60}=0.24$ ,  
248  $p=0.63$ ), and  $W_{Tot}$  (GLMM:  $F_{1,40}=0.01$ ,  $p=0.91$ ).

249

#### 250 **4. Discussion**

251 The aim of our study was to test the hypothesis that the locomotor pattern of  
252 an individual walking while carrying a load with another individual remains as  
253 pendular and economical as when he is walking alone. This hypothesis was tested by  
254 using the IPS model associated with a PAM to assess the economy of the locomotor  
255 pattern. The IPS represents the ideal situation of a pendulum displacement of the  
256 CoM and is considered as a model of energy saving during walking (Donelan et al.,  
257 2002). The PAM allowed us to compute the position of the CoM and to take into  
258 account the internal work (Moretto et al., 2016; Zatsiorsky and Seluyanov, 1983). To  
259 our knowledge, it is the first time that the economy of gait during collective load  
260 carriage in humans is investigated. Our work explores first the immediate adaptation  
261 of the individuals to load transport (WS vs CT1), then the adaptation to the task due  
262 to its repetition (CT1, CT2 and CT3).

263 When the RMSE and the amplitude of the vertical displacement of the CoM  
264 were compared between WS and CT1, no significant differences were found. The  
265 vertical displacement of the CoM of the individuals as a function of time in the two  
266 conditions thus followed the same sinusoidal pattern. These results are consistent  
267 with those of Holt et al. (2003) who found no significant difference in the amplitude  
268 of the CoM displacement for isolated individuals walking loaded (wearing a  
269 backpack) or unloaded.

270 To assess the consistency of the walking pattern with the IPS model, we  
271 computed the energy recovered according to Cavagna et al. (1977), i.e. in the sagittal

272 plane only, and the energy recovered in the three dimensions of the space,  $RR_{3D}$ , to  
273 take into account the fact that the potential energy can be transferred in forward as  
274 well as in transverse kinetic energy.

275         The value of  $RRs$  we found in the WS condition (59%) is close to that found  
276 by Bastien et al. (2016) in unloaded Nepalese porters and untrained individuals, i.e.  
277 61% for individuals walking at  $1.4 \text{ m}\cdot\text{s}^{-1}$ . Because the value of  $RRs$  increases in the  
278 CT condition compared to the trial in the WS condition, one can say that the walking  
279 pattern of the individuals was closer to a pendulum-like behavior when they were  
280 performing the collective load transport task than when they were walking  
281 separately. This result can be compared to that found by Heglund et al. (1995) in  
282 African women of the Luo tribe carrying loads on top of their heads. These authors  
283 found a  $RRs$  of 65% for unloaded women and a  $RRs$  of 68% for women carrying a  
284 load representing 10% of their body-mass (BM).

285         The values of  $RR_{3D}$  we found are very close to that found for  $RRs$ . Thus, one  
286 can conclude that the pendular behavior of the CoM is low in the frontal plane. Since  
287 this is observed in both the WS and CT conditions, one can assume that the walking  
288 pattern is not disturbed by the collective transport task, despite the physical link  
289 established between the two individuals. Finally, one should note that both  $RRs$  and  
290  $RR_{3D}$  increase between WS and CT1, suggesting an adjustment of the individuals to  
291 the load carriage task. Thus, it seems that the additional efforts linked to the  
292 coordination between individuals in the frontal plane do not disturb the energy  
293 recovered by each individual.

294         When the individuals are considered as a poly-articulated system and the  
295 contribution of each body segment can be assessed, the total mechanical work can be  
296 computed. Our results show that the mechanical work (whether internal, external or

297 total) did not change in CT1 compared to WS. Although Heglund et al. (1995)  
298 calculated mechanical work only in the sagittal plane, the values they found are  
299 comparable to ours for African women carrying loads of up to 20% of their body  
300 mass on top of their head. Our results are also close to those of Bastien et al. (2016)  
301 on individual Nepalese porters in which the changes in mechanical energy due to the  
302 lateral movements of the CoM were also neglected. In agreement with our findings  
303 these authors found that for individuals walking at a speed of 1.1 m.s<sup>-1</sup> the mass-  
304 specific total work is independent of the load carried, although it decreases with  
305 increasing loads for higher speeds ( $W_{\text{ext}}$  is stable but  $W_{\text{int}}$  decreases) (Bastien et al.,  
306 2016).

307         When comparing the three successive trials in the CT condition we observed  
308 an increase in the speed of the CoM, which could be considered a result of  
309 immediate adaptation to the collective task. Indeed, this could correspond to a better  
310 motor control of the task, i.e. for the same economy in mechanical output,  
311 individuals performed the carriage task faster during the first ones trials of collective  
312 carriage. As in Holt et al. (2003), this increase was accompanied by an increase of  
313 the CoM amplitude. There was also a trend to increase for both the  $RRs$  and  $RR_{3D}$   
314 (Fig. 3). The movements of the lower limbs could contribute to increase the  
315 pendulum like behavior of the overall CoM, and thus lead to a higher economy level.

316         Our study shows that the displacement of the CoM of an individual during the  
317 collective transport of an object follows the same sinusoidal pattern as that of an  
318 individual walking alone and unloaded. Moreover, during collective transport the  
319 pendular behavior of the CoM of the individuals increases, so that their locomotor  
320 pattern was more consistent with the IPS model. In parallel, we noted an increase in  
321 the speed and in the CoM amplitude during successive trials, which seems an

322 immediate adaptation to the collective transport situation. It could be also interesting  
323 to complete this analyze with more trials, to observe a possible effect of training.  
324 Finally, when the external and internal work are considered in 3D, we found that,  
325 despite the physical link between individuals, the total mechanical cost of  
326 locomotion did not change when walking alone and when walking while transporting  
327 an object with another individual. Our results are in accordance with the literature on  
328 load transport by single individuals and demonstrate the stability and economy of the  
329 locomotor pattern during load transport in general. As a caveat however, one should  
330 note that the object carried by the individuals in our experiment was relatively light  
331 and that one does not know whether the same results would be observed with heavier  
332 objects. In addition, a study of the metabolic cost and efficiency (Minetti et al., 2006)  
333 associated with collective load carriage could be helpful to complement the  
334 mechanical analysis presented here.

335         Today, carriage tasks are increasingly appearing as training exercises to  
336 improve physical capacities, e.g. in CrossFit training by team. Our study provides a  
337 better understanding of the effects of collective load carriage between two humans  
338 on locomotion and could be useful for improving the design of this type of training  
339 exercises. Our results could also be used for the conception of robots especially  
340 designed to assist humans (Cobot) in achieving difficult and strenuous tasks.

341

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345

#### 346 **Conflict of interest**

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

349

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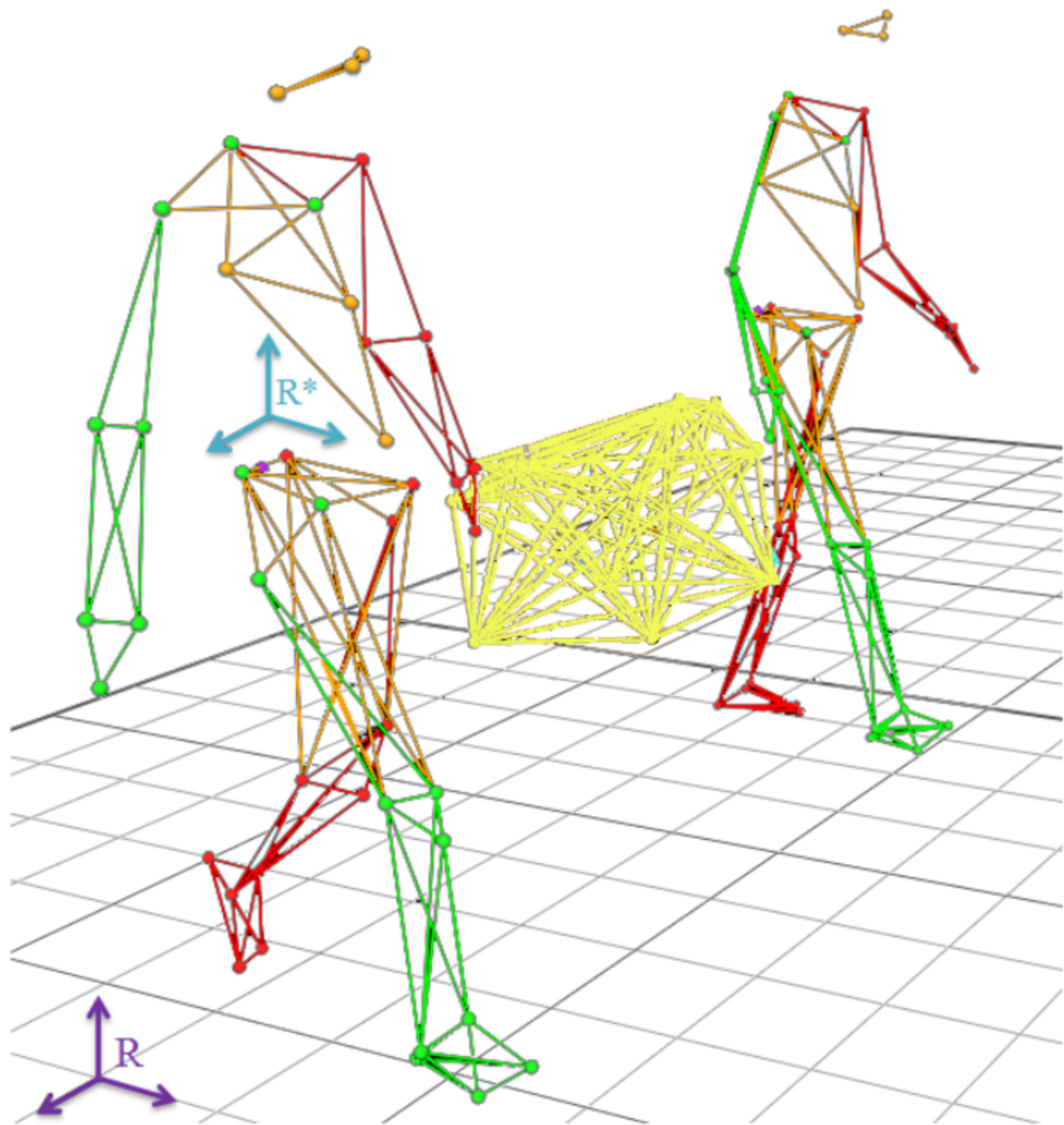
**Figure 1:** Example of a reconstruction of the participants and the box they carry on Nexus.

The sampling frequency was set at 200 Hz (filtered by a 4<sup>th</sup> order Butterworth filter and a 5 Hz cut frequency). The precision of the optoelectronic system was 1 mm for 1 m. The points correspond to the locations of the markers placed on the body according to De Leva's model (De Leva, 1996). The R\* referential (segments coordinate system) is represented in blue and the R referential (external coordinate system) in purple. The left side of the body is represented in red, the right side in green, the head, trunk and pelvis in orange and the box in yellow.

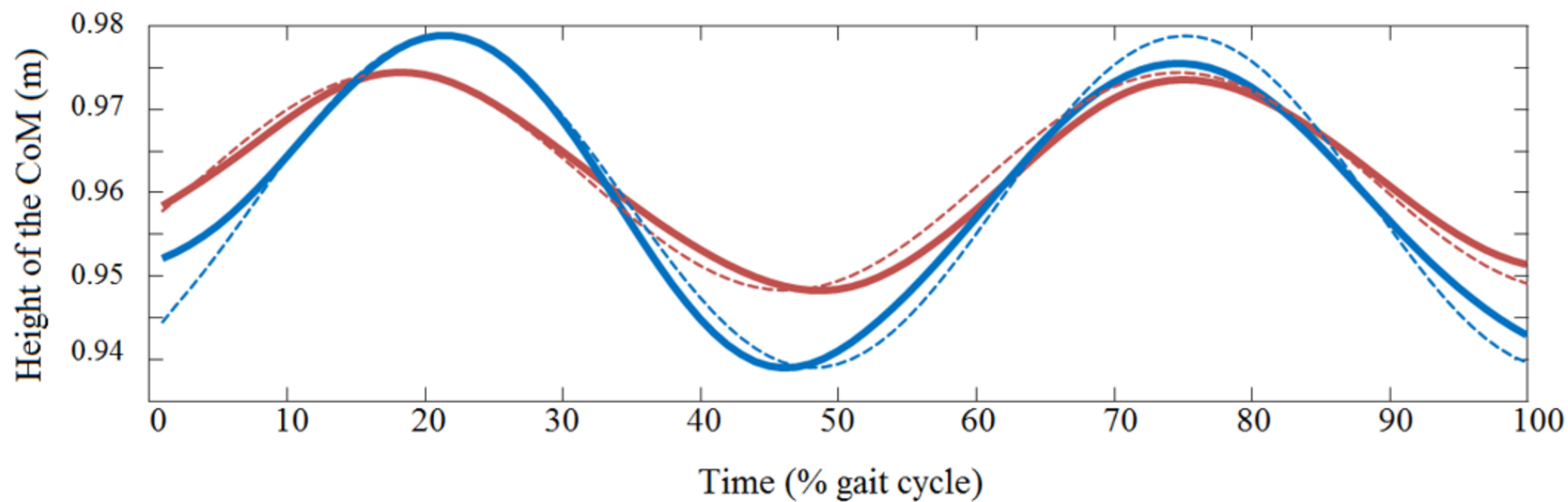
**Figure 2:** (A) Example of the vertical displacement of the CoM over a walking cycle for a pair of participants carrying a box of 13.41 kg while walking at a speed of 1.29 m.s<sup>-1</sup>. The continuous lines correspond to the experimental results and the dashed lines to the fitted sinusoidal function. (B) An example of the PAM organization over the different phases (DC: double contact and SC: single contact) of the walking cycle in the WS condition. The carrier hand of the participant located on the right side of the object is circled in blue. The time cycle was normalized by considering the duration of the gait cycle of each participant.

**Figure 3:** Mean  $\pm$  s.d. of (A) the amplitude of the vertical displacement of the CoM, (B) of the dimensionless RMSE (RMSE normalized by the amplitude of the vertical displacement of the CoM), (C) of the recovery rate in the sagittal plane and (D) of the recovery rate in 3D, for the trial in the WS condition and for the three trials in the CT condition ( $N=20$  in all trials). For the CT condition the values of the bars bearing the same letter (a, b) are not significantly different (GLMM). NS = no significant difference and \* = significant difference (paired  $t$ -test,  $p<0.05$ ).

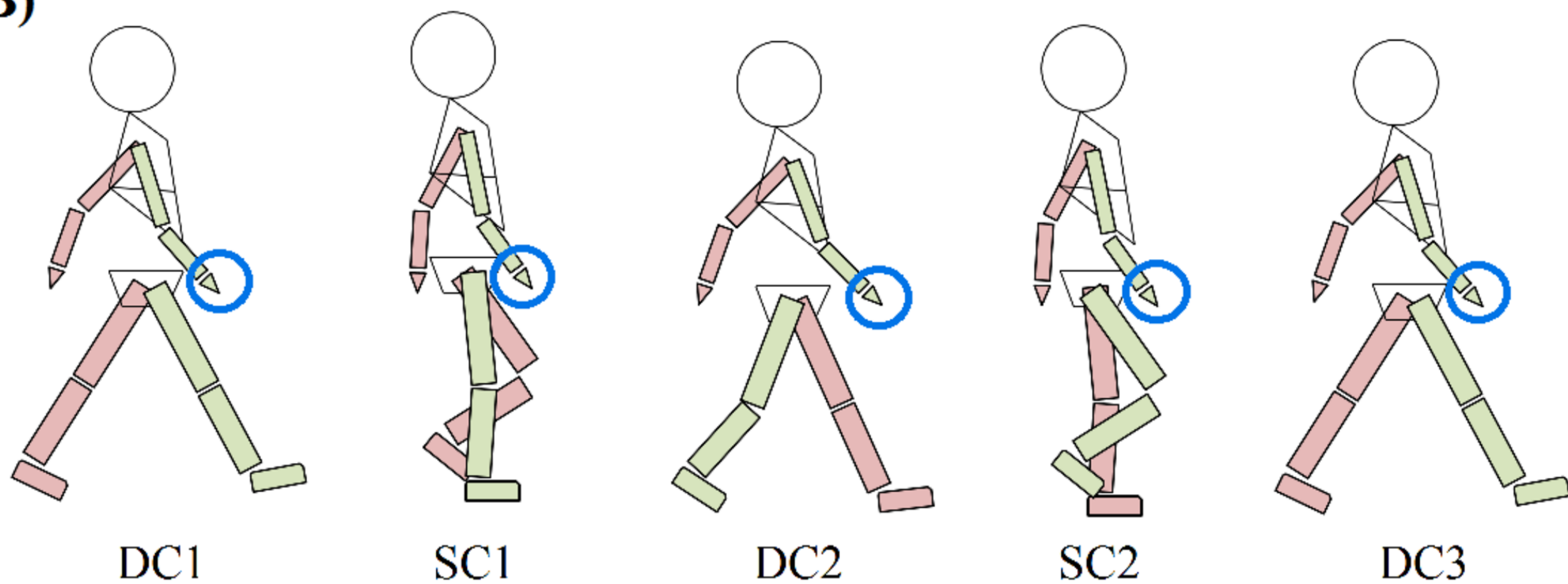
**Figure 4:** Mean  $\pm$  s.d. of the total, internal and external mechanical work divided by the distance of the gait cycle for the trial in the WS condition and for the three trials in the CT condition ( $N=20$  in all trials).

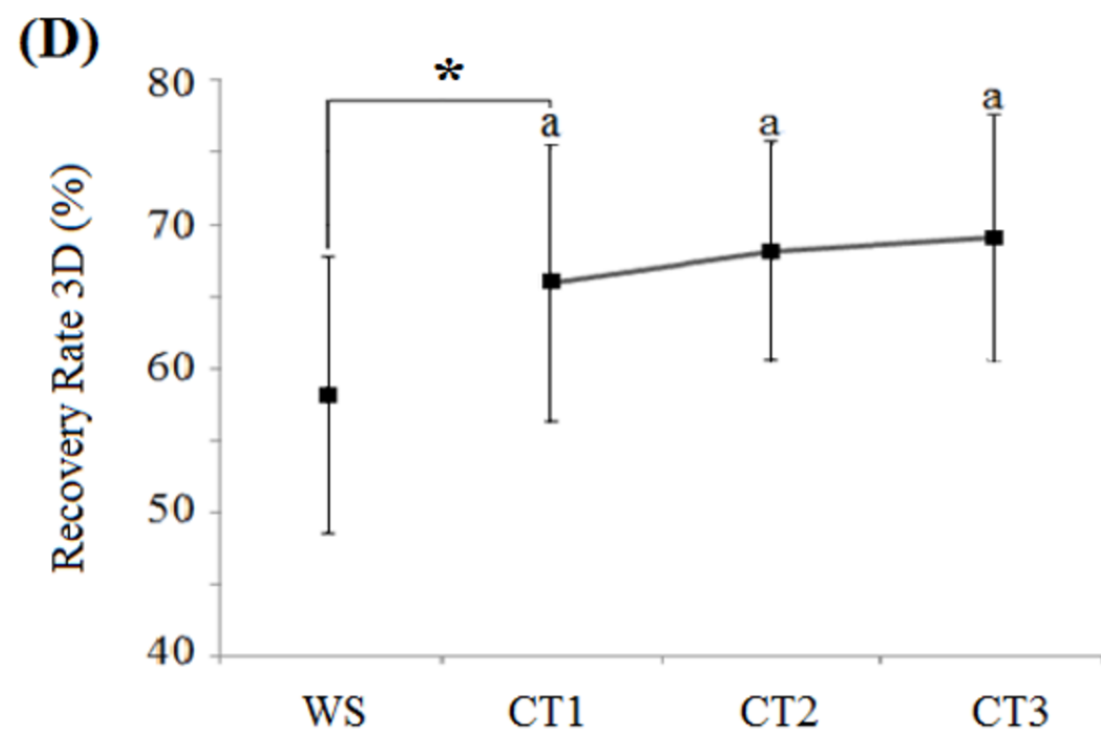
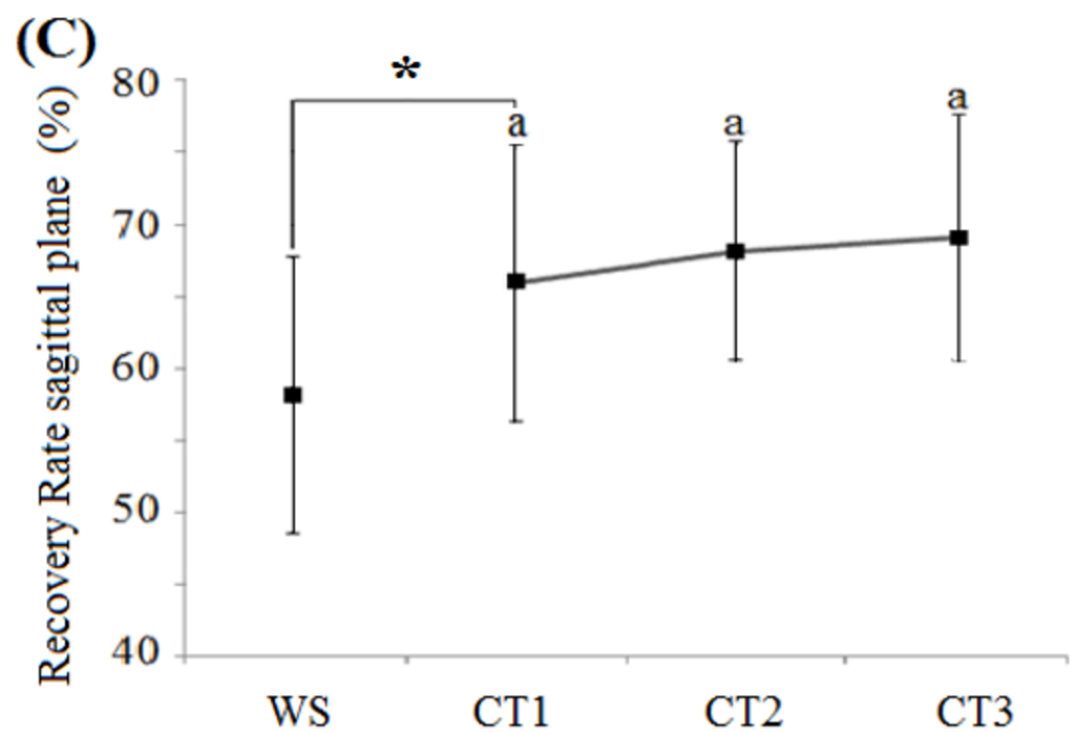
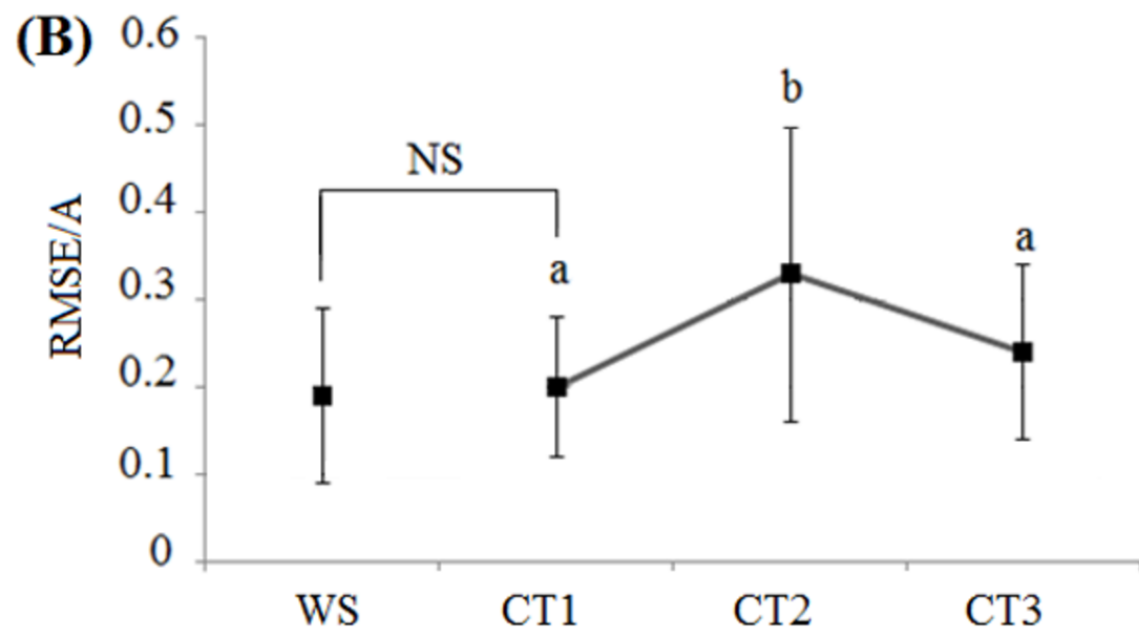
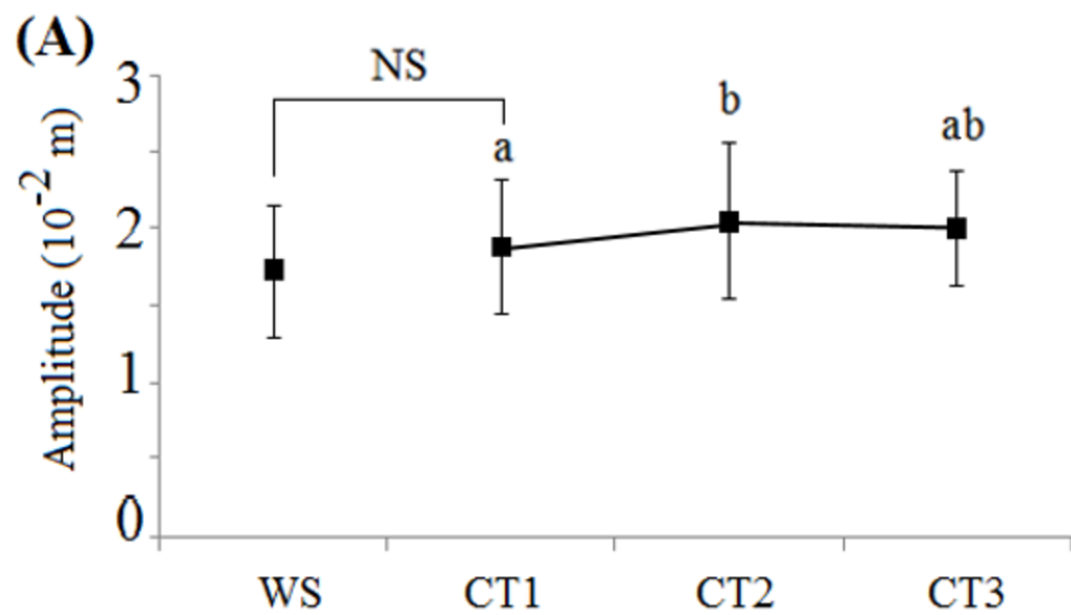


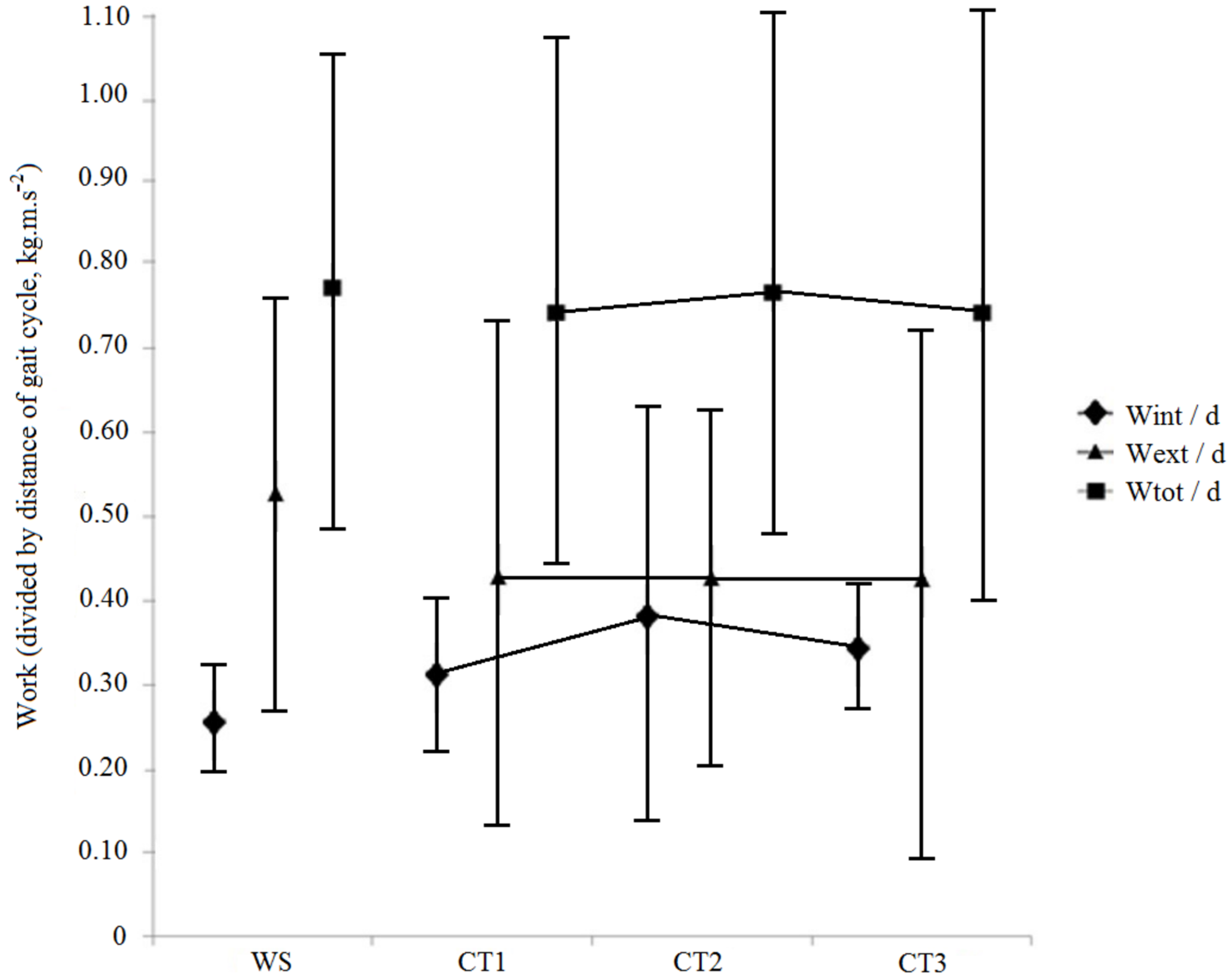
**(A)** — Participant located on the right side of the object  
— Participant located on the left side of the object



**(B)**









	<b>Age (yr)</b>	<b>Size (m)</b>	<b>Mass (kg)</b>
<b>Subject 1 (S1)</b>	25.40 (4.72)	1.77 (0.07)	74.78 (9.00)
<b>Subject 2 (S2)</b>	25.30 (2.71)	1.77 (0.05)	74.54 (12.38)

**Table 1:** Characteristics of the subjects: mean (standard deviation).