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# WALKING PATTERN EFFICIENCY DURING COLLECTIVE LOAD TRANSPORT.

Guillaume Fumery<sup>a,b</sup>, Laetitia Claverie<sup>a</sup>, Vincent Fourcassié<sup>a</sup>, Pierre Moretto<sup>a,\*</sup>

<sup>a</sup> *Centre de Recherches sur la Cognition Animale, Centre de Biologie Intégrative, Université de Toulouse, CNRS, UPS, France*

<sup>b</sup> *Physical medicine and rehabilitation center, MAS Marquiol, Toulouse, France*

## **Corresponding contact information:**

Pierre Moretto, PhD, *e-mail*: pierre.moretto@univ-tlse3.fr,

*phone number*: +33.5.61.55.67.31, *mail*: 118 Route de Narbonne 31062 Toulouse.

## **Authors information :**

Guillaume Fumery, PhD Student, *e-mail*: guillaume.fumery@univ-tlse3.fr,

Laetitia Claverie, PhD, *e-mail*: laetitia.claverie@univ-tlse3.fr,

Vincent Fourcassié, PhD, *e-mail*: vincent.fourcassie@univ-tlse3.fr,

*phone number*: +33.5.61.55.67.31, *mail*: 118 Route de Narbonne 31062 Toulouse.

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## **Highlights**

- Locomotion is as pendular in two subjects carrying a load as in single subjects.
- The center of mass displacement becomes more pendular in successive trials.
- Results propose values of mechanical economy for human-robot collaboration.
- Coordination of articular efforts between subjects needs to be explored.

## **Abstract**

*Background:* While the locomotor behavior of humans walking alone has been extensively studied, the locomotor behavior of humans transporting a load collectively is very poorly documented in the biomechanics literature. Yet, collective transport could find potential developments in other domains such as rehabilitation and robotics.

*Research question:* If collective load transport is made economically one could expect that the center of mass of the ensemble formed by several individuals and the load they carry has the same pendulum-like behavior as a single individual walking alone. The main objective of our study was to assess to what extent this is the case.

*Methods:* We recorded the 3D kinematics of movement of the body segments of ten dyads formed by two persons carrying a load together in three successive trials. The individuals carried the load, side by side, along a 13 meters straight trajectory. Then, the recovery rate of the center of mass of the ensemble formed by the two subjects and the load they carry (i.e. the rate of transfer between potential and kinetic energy) was computed.

*Results:* The values of recovery rate were similar to those found in the literature for individuals walking alone, showing that the external energetic exchanges occurring during collective transport are as efficient as those occurring in single gait. The recovery rate also increased in successive trials, suggesting an improvement of the performance with familiarization.

*Significance:* Our results demonstrate the ability of humans to collaborate efficiently for carrying a load. The values of recovery rate we found could be used as a benchmark for the control of collaborative robots.

**Keywords:** Gait; Collective behavior; 3D-Motion Analysis; Recovery rate; Center of mass.

## **1. Introduction**

The development of robots to assist humans in factories, hospitals and at home has become an important issue in ergonomic engineering [1]. Surprisingly, although research on human biomechanics is often used as a basis for robotic development [2], only few studies have been published so far on the biomechanical interactions between humans and robots during collective load carriage [3]. As a first step to understand the nature of these interactions, we thus decided to investigate the mechanical economy achieved by humans during a collective load carriage task.

The concept of mechanical economy has mostly been studied so far in single gait of unloaded individuals. It is based on the work by Cavagna et al. [4] who suggested that the low mechanical work achieved during walking in humans could be explained by the pendular displacement of the center of mass of the body leading the authors to model the body as an inverted pendulum system (IPS). Because it is pendular and thus induces a transfer between potential and kinetic energy along the walking cycle, the spontaneous walking pattern is considered as an efficient means of locomotion [4,5]. One had to wait the work of Heglund et al. [6] on African women for the first study on the effect of load carriage on the mechanical economy of walking. However, these authors worked on single individuals and did not extend their study to collaborative load transport, which is likely to affect walking in a very different manner.

In this study, we investigated whether two human individuals transporting an object collectively behave economically. We computed the center of mass (CoM) of the ensemble formed by a dyad of individuals and the load they carry. Then, we studied its displacement during a whole walking cycle at constant speed. High-resolution 3D tracking and reconstruction techniques of kinematic data [7] of the dyads allow to do this by representing each dyad as a Poly-Articulated Collective System (PACS), i.e. a poly-articulated system of multiple  $n$  rigid segments [8]. If the CoM displacement of the PACS

has the same pendulum-like behavior as the CoM of a single individual as described in the literature, the external work would be minimal for a constant speed.

## **2. Material and methods**

### *2.1. Population*

Twenty healthy male volunteers tested by pair (mean $\pm$ SD: individual 1 on the left side of the load: height = 1.77 $\pm$ 0.07 m, mass = 74.78 $\pm$ 9.00 kg; individual 2 on the right side of the load: height = 1.77 $\pm$ 0.05 m, mass = 74.54 $\pm$ 12.38 kg) performed successively three trials at spontaneous speed on a 13m-long walkway (Fig.1). The individuals walked side by side with a box (mass = 13.41 kg) they carried by two lateral handles. The mass of the box was close to 10% of the body-mass of the two individuals. This way we respected a level of activity practiced daily by the individuals, according to the definition of a non-interventional study of the CNRS bioethical office. Informed consent was obtained from all participants.

### *2.2. Experimentation*

Thirteen infrared (11 MX3 and 2 TS40) transmitter-receivers video cameras (Vicon©, Oxford metric's, Oxford, United Kingdom) were used to acquire the kinematic data of one gait cycle by trial. The Vicon calibrated volume (30 m<sup>3</sup>) was set in the middle of the walkway to record the walking patterns at stable speed. The gait cycle of the PACS was recorded from the first heel strike of individual 1 to the third heel strike of individual 2. Ninety-eight retro-reflective markers were placed on the PACS (i.e. 42 on each individual according to Wu et al. [9,10] and 14 on the box), and their positions were recorded at a frequency of 200 Hz (filtered with a 4<sup>th</sup> order Butterworth filter and a 5 Hz cut frequency). The kinematic analysis of the PACS was carried out with the software Vicon Nexus™ 1.8.5 (Fig. 1).

### *2.3. Computed parameters*

The De Leva Anthropometric tables [11] allowed us to estimate the mass  $m_i$  and the  $\text{CoM}_i$  of each segment and to assess the global CoM of the PACS (Fig. 1). The CoM of the PACS (Eq. 1) was computed as follows:

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

With  $\mathbf{G}_{PACS}$  the 3D position of the PACS CoM in the frame R (the global coordinate system),  $m_{PACS}$  the mass of the PACS,  $n$  the number of PACS segments (i.e. 16 segments per volunteer plus one segment for the box) and  $\mathbf{G}_i$  the 3D position of the  $\text{CoM}_i$  in the frame R (Fig. 1).

[Figure 1 near here]

Then, we computed with the same method as Bastien et al. [12] the forward kinetics, as well as the vertical and external work of the global CoM of the PACS. We assumed that the friction at the joints and ground contacts could be neglected.

The forward kinetics work ( $W_{kf}$ ) is the positive work to accelerate the CoM forwards, calculated as the sum of the increments of the forward kinetic energy ( $E_{kf}$ , computed on the y axis, Eq. 2) along the time curve with:

$$E_{kf} = \frac{1}{2} m V_{fG}(t)^2 \quad (2)$$

where  $m$  is the mass of the individual and  $V_{fG}(t)$  is the linear forward velocity of the CoM in the global coordinate system (R).

The vertical work ( $W_v$ ) is the positive work to move the CoM against gravity, calculated as the sum of the increments of the vertical kinetic energy ( $E_{kv}$ , computed on the z axis, Eq. 3) plus the potential energy ( $E_{pot}$ , Eq. 4) along the time curve with:

$$E_{kv} = \frac{1}{2} m V_{vG}(t)^2 \quad (3)$$

and

$$E_{pot} = mgh \quad (4)$$

where  $V_{vG}(t)$  is the linear vertical velocity of the CoM in R,  $g = 9.81 \text{ m.s}^{-2}$  is the module of the acceleration vector due to gravity and  $h$  the vertical height of the CoM position in R (z-component).

The external work ( $W_{\text{ext}}$ ) is the positive external work to raise and accelerate the CoM. It is computed as the sum of the increments of the external mechanical energy ( $E_{\text{ext}}$ , Eq. 5) along the time curve with:

$$E_{\text{ext}} = E_{\text{pot}} + E_{\text{kv}} + E_{\text{kf}} \quad (5)$$

Following Cavagna et al. [12], we computed the recovery rate ( $RR$ ) of the PACS CoM (Eq. 6) in the sagittal plane to obtain an indication of the amount of energy transferred between the potential and the kinetic energy: the closer the value of  $RR$  to 100%, the more consistent the locomotor pattern is with the IPS model [4,13,14,15].

$$RR = 100 \frac{W_{kf} + W_v - W_{\text{ext}}}{W_{kf} + W_v} \quad (6)$$

If the friction forces were to be neglected and the system was conservative, it would have a  $RR$  equal to 100 %.

#### 2.4. Data analysis

The data were analyzed with Matlab R2016b© and R 3.4.3. After checking for normality, a paired  $t$ -test was used to compare the  $RR$  between successive trials. The significance threshold was set at 0.05.

### 3. Results

The  $RR$  was not significantly different between the first and second trial ( $t=0.57$ ) but increased by 15% between the second and third trial ( $t=-2.73$ ,  $p=0.02$ ) and by 11% between the first and third trial ( $t=-2.85$ ,  $p=0.02$ ) (Fig.2). The variability of the  $RR$  also decreased from trial 1 to trial 3, as shown by the value of the relative standard deviation (RSD = 23, 36 and 14% for trial 1, 2 and 3 respectively).

[Figure 2 near here]

### 4. Discussion

In this study, we investigated the pendular displacement of dyads of individuals carrying a load collectively. To do this, we first computed the position of the global CoM of the PACS. Then, we computed an index commonly used in studies of individual locomotion, the recovery rate, to evaluate the pendular displacement of the global CoM during three successive trials of the same dyads of individuals.

The *RR* was not significantly different between the first and second trial (mean $\pm$ CI<sub>0.95</sub>: 60.25 $\pm$ 7.59 and 56.20 $\pm$ 9.19%, respectively). These values are close to those found by Bastien et al. [13] on unloaded Nepalese porters and untrained individuals (*RR*=61%). Thus, the displacement of the CoM of the PACS is as pendular as that of the CoM of single individuals walking alone [13], highlighting a comparable transfer between potential and kinetic energy. Further research focusing on the articular efforts deployed by each individual during the transport would be required to understand the mechanisms underlying this result.

Our results also show a better pendulum-like behavior of the PACS and a lower variability between the ten dyads of individuals in the third trial, suggesting an improvement of the performance with familiarization.

Our approach allows to quantify the efficiency of a dyad of individuals carrying the same object and to propose a value of recovery rate that could be integrated to define the range of parameter values of a pattern generator designed for collaborative robots [16,17].

### **Conflict of interest statement**

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

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## References

- [1] M.A. Goodrich, A.C. Schultz, Human-Robot Interaction: a survey, *FTHCI 1* (2007), 203-275.
- [2] C. Vassallo, A.H. Olivier, P. Souères, A. Crétual, O. Stasse, J. Pettré, How do walkers behave when crossing the way of a mobile robot that replicates human interaction rules? *Gait Posture* 60 (2017), 188–193.
- [3] A. Bussy, P. Gergondet, A. Kheddar, F. Keith, A. Crosnier, Proactive behavior of a humanoid robot in a haptic transportation task with a human partner. In: *IEEE (Ro-Man)*, Paris, France, September 9-13, 2012.
- [4] G.A. Cavagna, F.P. Saibene, R. Margaria, External work in walking, *J. Appl. Physiol.* 18 (1963), 1-9.
- [5] J.M. Donelan, R. Kram, A.D. Kuo, Simultaneous positive and negative external mechanical work in human walking, *J. Biomech.* 35 (2002), 117-124.
- [6] N.C. Heglund, P.A. Willems, M. Penta, G.A. Cavagna, Energy-saving gait mechanics with head-supported loads, *Nature* 375 (1995), 52-54.
- [7] L. Tesio, D.L.C. Detrembleur, The 3-D motion of the centre of gravity of the human body during level walking. I. Normal subjects at low and intermediate walking speeds, *Clin. Biomech.* 13 (1998), 77–82.
- [8] P. Moretto, D. Villeger, A. Costes, B. Watier, Elastic energy in locomotion: spring mass vs. poly-articulated models, *Gait Posture* 48 (2016), 183–188.
- [9] G. Wu, S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D.D. D’Lima, L. Cristofolini, H. Witte, et al., ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--Part I: ankle, hip, and spine, *J. Biomech.* 35 (2002), 543–548.

- [10] G. Wu, F.C.T. van der Helm, H.E.J. Veeger, M. Makhsous, P. Van Roy, C. Anglin, J. Nagels, A.R. Karduna, K. McQuade, X. Wang, et al., ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand, *J. Biomech.* 38 (2005), 981–992.
- [11] P. De Leva, Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters, *J. Biomech.* 29 (1996), 1223-1230.
- [12] G.A. Cavagna, H. Thys, A. Zamboni, Sources of external work in level walking and running, *J. Physiol.* 262 (1976), 639-657.
- [13] G.J. Bastien, P.A. Willems, B. Schepens, N.C. Heglund, The mechanics of head-supported load carriage by Nepalese porters, *J. Exp. Biol.* 219 (2016) 3626–3634.
- [14] N.A. Gomenuka, R.L. Bona, R.G. da Rosa, L.A. Peyré-Tartaruga, Adaptations to changing speed, load and gradient in human walking: Cost of transport, optimal speed, and pendulum, *Scand. J. Med. Sci. Spor.* 24 (2014), e165-e173.
- [15] P.A. Willems, G.A. Cavagna, N.C. Heglund, External, internal and total work in human locomotion, *J. Exp. Biol.* 198 (1995), 379–393.
- [16] M. Peshkin, E. Colgate, Cobots, *Ind. Robot.* 26 (1999), 335-341.
- [17] D. J. Agravante, A. Sherikov, P-B. Wieber, A. Cherubini, A. Kheddar. Walking pattern generators designed for physical collaboration. In *IEEE Int. Conf. on Robotics and Automation*, France, May 16-21, 2016.

Figure 1. Reconstruction of the individuals and the box they carry on Vicon Nexus™. The left side of the body is represented in red, the right side in green and the head, trunk and pelvis in orange. The points correspond to the locations of the markers. The circled crosses represent the CoM of individual 1 (red), individual 2 (blue), the box (green) and the PACS (grey). The sagittal plane is in purple in the R referential (external coordinate system), with x the medio-lateral axis, y the antero-posterior axis and z the vertical axis.

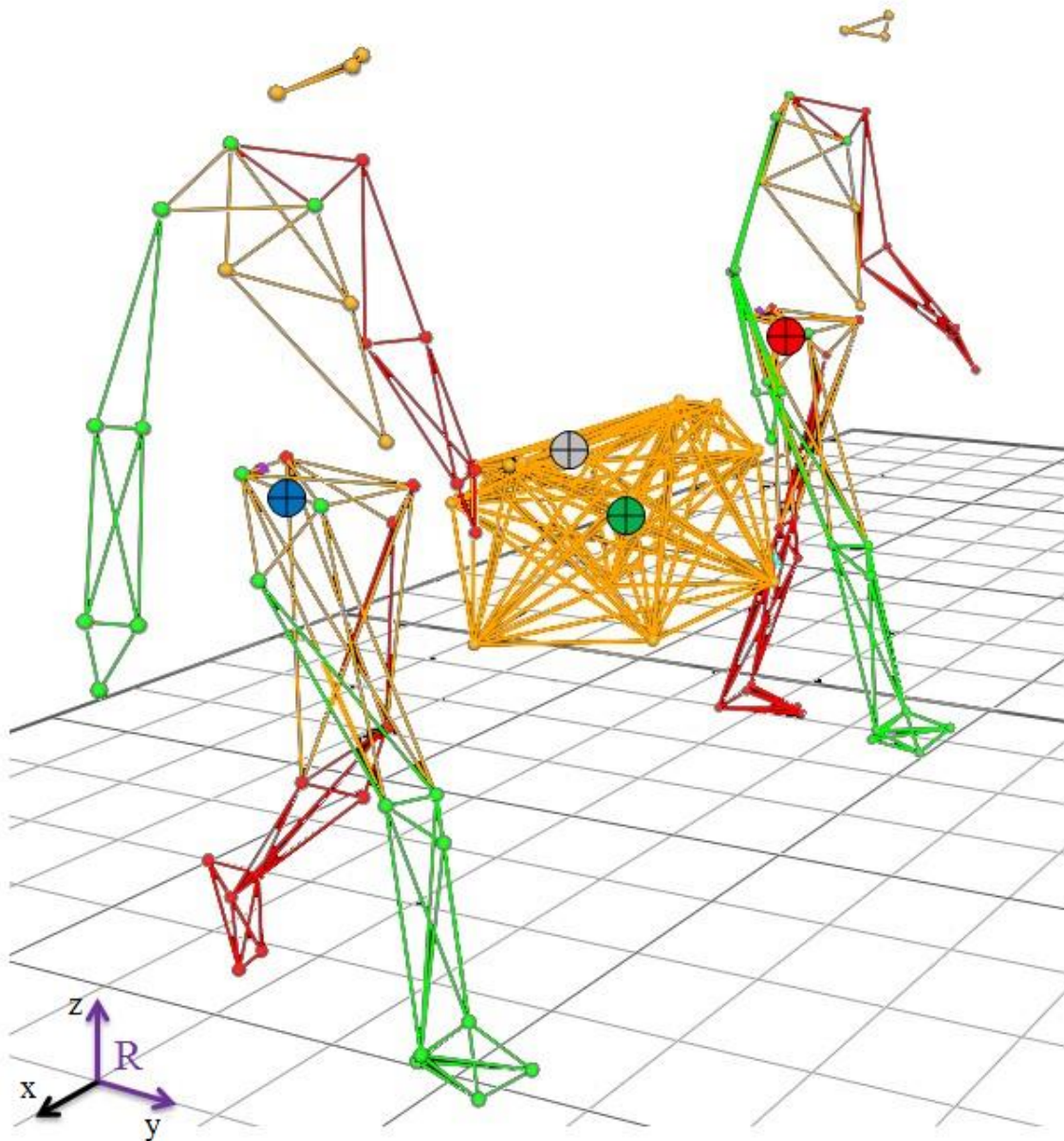


Figure 2. Mean  $\pm$  SD of the *RR* of the PACS CoM for the three successive trials ( $N=10$  in all trials). The bars sharing the same letters indicate values that are not significantly different ( $p>0.05$ ).

